PART I: ASSESSMENTS OF HANDS-ON LEARNING AND LECTURE.

PART II: STABILITY AND DRAG REDUCTION IN STEADY CAPILLARY FLOW THROUGH HYDROPHOBIC CHANNELS WITH MINIMAL HELICAL WIRE SUPPORTS.

By

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PART I: ASSESSMENTS OF HANDS-ON LEARNING AND LECTURE.

PART II: STABILITY AND DRAG REDUCTION IN STEADY CAPILLARY FLOW THROUGH HYDROPHOBIC CHANNELS WITH MINIMAL HELICAL WIRE SUPPORTS.

Abstract

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Abstract

The expertise differential between instructor and student provides adequate potential for flow of expertise from the former to the latter during instruction. However, the intrinsic and extraneous cognitive loads (resistances to learning posed by the topic and instructional design/implementation, respectively) need to be minimized. Multimedia learning and hands-on interactive learning are believed to reduce cognitive load over straight lecture. Several instructional configurations were compared in terms of important learning outcomes. Overall, students perceived that group miniaturized equipment-mediated instruction helped them more than lecture in terms of schema formation and aspects of competence-based education like group dynamics and hands-on skills.
Stability and drag reduction during steady capillary fluid flow through hydrophobic extension springs were studied numerically and experimentally. Large-bore capillary channels formed from these springs are envisioned for phase separation and liquid-gas contacting in space and for small-scale terrestrial capillary transport. A practical realization of a structure with alternating transverse slip and no-slip boundaries that can give relatively large slip fractions and a large ratio of the length of slip sections to tube radius is a cylindrical capillary channel supported by a stretched hydrophobic spring. Some aspects of the flow in such a channel can be approximated by flow in the corresponding axisymmetric array of wire rings. Flow in such a channel is modeled by the finite element method on a periodic domain obtained by matching velocity fields at the extremities of the period. Drag reduction, measured by the slip length is found to increase with increasing pitch of the period and with increasing fraction of slip boundary, and to decrease with increasing roughness of the composite wire-plus-meniscus boundary and Reynolds number above 50. Overall, the highest drag reduction is found to occur for the highest contact angle studied (178°), Reynolds number below 50 and a smooth no-shear boundary.

Stability and drag reduction during flow was studied experimentally in hydrophobic 1/4-inch and 1/8-inch springs. The ranges of stable pressures in the hydrophobic channels decreased with pitch and channel diameter. Consequently, relatively large flows up to 630 mL/min and slip lengths up to 140 μm were achieved at small pitches.
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Human Cognition and Cognitive Load Theory

Group learning, Cognitive Load Distribution and Motivation

Multimedia Learning and Cognition

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Dedication

I dedicate this work to all those who subscribe to Knowing, the endless journey.
CHAPTER ONE

INTRODUCTION

This section presents a brief introduction to the manuscripts that make up this dissertation. The brevity used here is justified because each manuscript contains its own more detailed introduction.

This dissertation, comprising five manuscripts and parts of a sixth one as the other chapters, is divided into two parts: engineering education and a technical component. It is comprised of three educational manuscripts, two technical manuscripts and my contributions to a sixth technical manuscript on which I will be the second author. The main theme that runs through the two parts of this dissertation is that of resistance reduction. In the educational work, a reduction of resistance to cognition and in the technical part a reduction of resistance to fluid flow. The dissertation will be arranged by manuscripts according to the order below.

The main theme in the educational papers is interpedagogical differences between a passive and a more active approach in terms of cognitive and affective outcomes.

The first educational paper is titled ‘Addressing Student Learning Barriers in Developing Nations with a Novel Hands-on Active Pedagogy and Miniaturized Industrial Process Equipment: The Case of Nigeria’. It has been published in the International Journal of Engineering Education (IJEE). The paper focuses on a comparison of learning outcomes between a passive lecture (control) and an active pedagogy, Hands-on Active Learning (HAL) which is a subset of a broader pedagogy dubbed CHAPL (Cooperative Hands-on Active Problem/Project-Based Learning). Based on Kolb’s experiential learning model and the seven principles of good
practice in undergraduate education, we sought to examine how HAL would impact student’s learning, motivation and their perceptions on how it differs from straight or “traditional” lecture.

The lecture group experienced a passive instructor-controlled lecture on extended heat exchanger concepts and skills while the HAL group experienced the same topic using equipment-mediated group work with the instructor serving as a facilitator. Although both groups improved post-instruction, no significant difference was found in cognitive gains using a 5-question multiple-choice test built around extended area heat exchanger concepts. However, a survey administered to students indicate that they believed HAL was more useful for inculcating the seven principles of good practice in undergraduate education (student-student interaction, instructor-student interaction, active learning, more time on task, prompt feedback, high expectations and diverse approaches to cognition) in addition to better visualization and retention of ideas, and preparation for professional work. Interviews of faculty members also support the advantages inherent in the addition of more student-engaging active components to classroom instruction. In conclusion, the miniaturized industrial equipment or Desktop Learning Module (DLM) used was found to be well suited for in-class use in large classes in developing countries because of fast dynamics, self-contained design (long battery life (~ 3 hours), hot and cold water tanks and built-in display electronics) which make it useful in infrastructure-challenged climes. The processes and materials involved in the HAL implementation are also believed to better help learners build professional skills.

The second educational paper is titled ‘A Tale of Two Pedagogies-Comparing Lecture and Active Learning in a Fluids and Heat Transfer Class ’. It is formatted in accordance to Advances in Engineering Education (AEE) journal guidelines (www.asee.org). The paper examines outcomes for various topics in a Fluid Mechanics and Heat Transfer (FMHT) Class, some of
which were taught using a CHAPL approach and some through straight lecture. Because this was a field study in a class taught by another professor, assumptions were made about the equivalence of topics taught using the two different pedagogical approaches. Topics were assumed equivalent because they contained similar concepts in architecturally different miniaturized industrial equipment. For instance the Pitot tube (a lecture topic) was assumed equivalent to a Venturi meter or an orifice meter (CHAPL topic) because they both measure flow using interconversions of pressure and velocity. Based on the cognitive dimensions of Fink’s taxonomy and the principles of social constructivism and experiential learning we sought to discern a difference between each cognitive dimension for both pedagogies. A rubric designed based on Fink’s cognitive dimensions of Foundational Knowledge, Application and Integration was used to rate the different assignments for groups that experienced the different pedagogies. The assignments were found to be unmatched because the lecture group was assigned textbook problems (which incidentally had a readily available solution manual) while the CHAPL group was assigned a well-designed worksheet that elicited more cognitive processing than textbook problems but did not have solutions available. Because of this quandary, a comparison was made between a final exam question based solely on material covered in the lecture on one hand, and three final exam questions based on materials covered in both lecture and CHAPL topics (composite). No difference was found between the lecture question and the composite questions separately. However, a survey administered showed that most students perceive in addition to other things, that CHAPL helped them more with the application dimension of cognition in problem solving while straight lecture helped them learn foundational knowledge better. There was no clear consensus on which of the pedagogies helped them integrate FMHT ideas better. We also learned some useful facts and skills during the convergent participation process
involving several professors experienced in teaching the class for development of the rating rubric. In addition to other things, we negotiated what exactly should be considered foundational knowledge, application or integration in the FMHT domain and what evidence to look for in a poor and an excellent answer. In addition, students proffered suggestions for improving future implementations of CHAPL. These include structured pre-activity lectures to prepare them more for the lecture activity, more time to complete the in-class experiments, and increase in credit from 2 to 3 because of what they perceive as increased workload due to the extra preparations required of them.

The third educational paper is titled ‘Pedagogical Influences on Learning Gains in a Fluid Mechanics and Heat Transfer Class’ and is formatted according to Journal of Engineering Education (JEE) guidelines. It represents a more tightly controlled experiment where two groups, the HAL (experimental) and the multimedia-aided lecture (control), were taught the same topics by the same professor, assigned the same assignments and rated by the same raters anonymously.

Based on theories underlying Human Cognitive Architecture and the Cognitive Load Theory of multimedia, we expected to discern an intergroup difference in Fink’s cognitive dimensions and/or affective outcomes using different assessment artifacts. We used post-instruction improvement in Fink’s dimension scores as an indirect, objective measure of cognitive load reduction. We hypothesized that there would be greater reduction in cognitive load in the HAL than in the multi-media lecture group because of the collaboration and use of real equipment by the former. Cognitive load here refers to the resistance to learning imposed by the learning presentation format (extraneous cognitive load) and the difficulty of the material to be learnt (intrinsic cognitive load). However, as with the other studies, no significant difference could be
discerned in the gains for most of the assignments rated which suggested a similar reduction in
cognitive load by both pedagogies. In the few cases where a slightly significant difference was
observed, it was in favor of the lecture group. An examination of the questions for which the
multimedia lecture group performed significantly better, revealed that they pertained to factual
knowledge, recipes for solving problems with no direct relation to the DLMs, and to the use of
charts. This finding is in line with suggestions in the extant literature that lecture is better than
interactive engagement for conveying quick facts. Interestingly, analysis of the end of class
survey and comments showed that more students perceived that the HAL helped or would have
helped better than lecture to build and solidify their cognition. They also indicated that the HAL
was better than lecture for achieving outcomes of competence-based education such as
 collaborative skills and analysis of real systems.

It was concluded from the cognitive outcomes that the two pedagogies seemed to have reduced
cognitive load by the same amount and that the cognitive advantage in the HAL group appeared
redundant because the task was not complex enough to make efficient use of the said advantage.
It is believed that a lower class (e.g. freshmen) could make more efficient use of this
 collaborative advantage because of their lower position on the expertise trajectory. A more
complex task would also increase the efficiency of collaboration. In addition, because of the
strong support for HAL perceived from the survey, type I & type II errors cannot be overlooked.
Type I error occurs when a test finds a difference that does not actually exist while type II error
occurs when a test fails to identify a difference that actually exists. The occurrence of these
errors can be confirmed or refuted by increasing the statistical power of the test through
increasing the population size or through a rigorous power analysis.
The main theme in the technical research is drag reduction (quantified by the slip length) in fluid flow through channels with minimal helically supported two-fluid interfaces. A subtheme that is very important to flow is the static stability and compliance of the said interfaces. Compliance in this usage refers to the change in volume with pressure change. A more compliant channel will have a higher change in volume for a fixed change in pressure than a stiffer one. The static stability is important as it dictates the pressure extremes in pressure-driven flow while the compliance is important because a more compliant channel will give a higher pressure jump across the liquid-air interface and thus a higher surface curvature which implies more roughness for a particular change in pressure. This increase in roughness can lead to stagnation zones within the roughness which degrades boundary slip. For water-air interfaces supported on a highly water-repellent (superhydrophobic) helical wire, the statics, flow phenomena and metrics involved are very interesting indeed.

The three technical manuscripts contained in this dissertation are formatted in accordance with the journal Physics of Fluids guidelines (www.aip.org).

The first technical paper is titled ‘Flow in helical channels with periodic slip and no-slip boundaries’. It pertains to fully-developed, open-channel flow and consequent drag reduction in a simplified model of the single helix structure used in the experiment. The primary hypothesis was that there would be significant drag reduction mainly because of the large scale reduced-shear or essentially shear-free water-air portions of the geometry. The dimensionless model parameters varied are: Reynolds number, pitch, wire radius, contact angle (wetting), and Laplace pressure (i.e. the pressure drop across a liquid-gas interface supported by surface tension). This simplified model predicted monotonous increase of effective slip length with pitch, a flat effective slip length vs. Reynolds number profile up to Reynolds number of about 100 followed
by a gradual dip, increase in effective slip with decrease in dimensionless wire radius in the range 0.18-0.02. The relationship between effective slip and Laplace pressure is more complicated because of the balance between roughness and pitch which dictate the maximum slip. Also, the effective slip in the wetting regime ($\theta_c < 90^\circ$) appears static because the increase in contact angle in that range is inadequate to overcome the form drag due to immersion of the wire. The effective slip however increases with increase in contact angle above neutral wetting ($90^\circ$). In conclusion, significant effective slip was discerned even though it is lower than that of the Lauga and Stone model (a periodic slip, no-slip cylinder). This is due to the added roughness in our model from either or both of the wire and interface (meniscus) curvatures.

The portion of the hydrostatics paper, titled ‘Hydrostatic stability in springs with highly water-repellent walls in normal gravity’ included in this dissertation pertains to compliance and stability investigations in horizontally configured channels supported by highly water-repellent helical wires at different Bond numbers. These measurements were made on two sizes of springs (1/4 and 1/8-inch) coated with hydrophobic sol-gel at different pitches (and therefore different Bond numbers). The Bond number quantifies the relative importance of gravitational forces compared to surface tension forces. The more superhydrophobic portions of the channels show lower diameters as expected and as evident from the smoothed axial diameter profiles. Also the channels become more compliant (show higher change in volume (diameter) with unit change in pressure) as the pitch is increased as can be readily seen from the spacing of the smoothed diameter profiles as the static pressure is increased. The channels are observed to fail at lower pressure for larger pitch and the do so at more wetting points. Qualitative agreement of the compliance data with the Bernate-Thiessen theoretical curves was demonstrated. However, in contrast to Oelerich’s data from a 300 $\mu$m spring, quantitative agreement remains
undemonstrated probably due to gravitational effects in these 10 and 20 times larger diameter springs. In conclusion, a non-monotonous diameter profile has been demonstrated in these springs coated with a hydrophobic sol-gel suspension. The more wetting portions of the spring show higher diameters and higher compliance. Also the compliance in the same regions appear uniform (uniform increase in diameter with pressure) except close to the failure point. The channels generally fail at the weak link in the system, which would be the most wetting part for a spring with uniformly distributed pitch.

The second full technical paper is titled ‘Drag reduction for flow in superhydrophobic springs’. It pertains to flow in the superhydrophobic channels mentioned in the paper section on hydrostatics. Capillary-driven flows in these relatively larger channels (minichannels compared to microchannels) have been demonstrated for a range of Reynolds number encroaching on the transition region. The highest Reynolds number achieved in the smaller 1/8-in spring is about 900 while a Reynolds number of about 2400 was achieved in the larger 1/4-in spring, all based on the inner (hydraulic) diameters of the channels. The primary hypothesis in this work was that a slip length (relative to a closed pipe of the same hydraulic diameter) within those reported in the literature for macroscopic effective slip structures (e.g. holes, trenches and cavities) could be measured in our stretched springs within limits of systematic and other experimental errors. Flow experiments were performed for small pitch and large stable pitch for aspect ratios less than 100 for the larger diameter spring and greater than 100 for the smaller diameter spring, within the limits of the experimental system configuration. Pressure drops between the channel inlet and outlet were measured at different flow rates and converted to dimensionless pressure gradients using the pressure gradient in fully-developed laminar flow for a closed pipe of same hydraulic diameter as the scaling factor. These were compared to theoretical results for a pipe of the same
ID as the channel to discern any reduction in channel pressure gradient. Because of flow development issues in channels with alternating slip and no-slip boundaries, an effective slip model was set up in COMSOL (a commercial finite element software) with the same aspect ratio and diameter as the experiment and the effective slip length on the boundary varied until the results closely matched the experimental data. The range of model-generated effective slips which matched the data was then taken to be the range of experimental slip lengths measured. Thus slip lengths in the vicinity of 26 μm were measured for the 1/4-inch spring and 70-140 μm for the 1/8-inch spring within limits of experimental error. These values are on the high end of those reported in the extant literature. In conclusion therefore, a significant drag reduction (up to 40%) and thus significant slip length has been discerned in our channels using an indirect measurement technique (pressure drop). This suggests potential usefulness of these channels for drag reduction in fluidic networks. Also, because of the high flows (up to 93 mL/min for the 1/8-inch spring and up to 628 mL/min in the 1/4-inch spring) through these channels, high liquid mass velocities between 27,406 lb/ft²hr and 47,748 lb/ft²hr could be sustained in microgravity liquid-gas contacting.
CHAPTER TWO

Addressing Student Learning Barriers in Developing Nations with a Novel Hands-on Active Pedagogy and Miniaturized Industrial Process Equipment: The Case of Nigeria

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Abstract

There is a global need to implement modern educational pedagogies. For developing nations, class size, utilities infrastructure, and a deeply entrenched lecture-based teaching paradigm are additional challenges. Our fundamental hypotheses are that classroom logistics in a transport class can be modified to use a novel pedagogy incorporating a Desktop Learning Module (DLM) for effective Hands-on Active Learning (HAL) in a developing nation and that enhanced learning will take place. HAL was compared to Lecture in a 127-student, 300-level Chemical Engineering (CHEN) class and assessed through multiple-choice quizzes, and survey questions based on the Seven Principles for Good Practice. Follow-up faculty interviews were conducted to explore additional impact related to the introduction of HAL. For side-by-side comparison of the two pedagogies the class was split into two groups. These studies revealed there was significant but equal improvement in conceptual understanding for both the HAL (n = 59) and Lecture (n = 68)
groups. However, surveys reveal HAL is in better alignment with Principles for Good Practice in undergraduate education. Faculty interviews add supportive evidence that students who experience the new pedagogy do better than those who do not. There is also an apparent spread effect suggesting that the introduction of cooperative learning strategies influenced faculty teaching and student learning behaviors. Also, the DLM device has features that encourage its adoption such as fast response, portability and suitability for interfacing with a student group. The introduction of HAL pedagogy has important implications and holds strong promise in challenged learning environments as found in Nigeria. The DLM is found to be well suited for this environment.

**Keywords:** educational pedagogies, hands-on active learning; global; challenged environment;; Principles for good practice

1.0 Introduction

Enhancements of educational delivery using active and hands-on learning have been reported in numerous science and engineering education articles [1-5]. These articles posit that visual and tactile learning experiences have distinct advantages over a merely aural one [6-7]. This is particularly important in engineering because of the applied nature of the field. Kolb’s experiential model [8-9], recognized as one of the suitable pedagogical models for engineering education [2], postulates active experimentation (or hands-on experience) as one of the four complementary stages of learning construction. This aspect of active experimentation has been mostly relegated to separate laboratory classes in engineering education with some attendant disadvantages such as student lack of autonomy in the learning process and less time for focused interactive discussion on specific concepts. Another incentive for studies in hands-on active engagement is that it
has been identified as a precursor to persistence of students in engineering major as well as playing a role in student migration from other majors [10-11].

Hands-on active learning has been implemented in a variety of ways including virtual laboratories [12-13], remote laboratories [14-15], seminar-type demonstrations [16], full-scale laboratory activities [2, 17] and in-class activities with full student involvement [18], each with its associated pros and cons. In-class learning activities are thought to be unique because they facilitate simultaneous learning of engineering concepts and skills [18-19] instead of serial learning as would occur when lecture and laboratory are separated [2, 4, 20-21]. However, some challenges in implementing in-class active hands-on learning have been identified [18] and are more pronounced in developing countries such as those on the African continent. These challenges include [22] very large student numbers where, even for upper division courses, there can be as many as 100-500 students all in an overcrowded room with insufficient seating, curricular limitations, time constraints, severe budget constraints, utilities that are unreliable, and use of dysfunctional pedagogies such as straight dictation. In addition to these challenges, lecturers have minimal preparation time because of the paucity of staff at the PhD level, which is a fallout of African universities expansion without the commensurate training of high level staff [23]. These challenges must be considered when creating innovative solutions; obviously, if they can be circumvented then the benefits of in-class experiential learning such as enhanced interaction and retention can be realized.

The drive for international collaboration in the reform of engineering education [24] and the search for global competency in engineering [25] necessitate international cooperation in engineering education research. Because many developing nations have advantages of abundant ma-
Material and human resources [26-27], as is the case with Nigeria where the present study is taking place, they may be uniquely positioned to benefit from such collaboration with advanced countries for human capacity building so they can become globally relevant. The present paper summarizes an attempt to address student learning barriers in the Chemical Engineering program at Ahmadu Bello University in Zaria Nigeria where, during a Fulbright Exchange by co-author Van Wie, we used miniaturized industrial process equipment otherwise called Desktop Learning Modules (DLMs) to reinforce a new pedagogy based on Kolb’s model [8] and the Seven Principles for Good Practice (7 PGPs) in Undergraduate Education [28]. The class of interest CHEN 302 otherwise titled “Physical Transport Phenomena II: Heat Transport” is traditionally a sequel to CHEN 301 or “Physical Transport Phenomena I: Momentum Transport” and is traditionally taken in the third year of a 5-year program. We assess the impact of using DLMs with the new pedagogy to assist in teaching heat transport phenomena principles of relevance to the education of chemical and mechanical engineers in light of very large class sizes, reduced availability of utilities and unfamiliarity of students and lecturers with new learning styles. Furthermore, we assess the impact on conceptual understanding compared to traditional lectures, and use a survey instrument with construct validity [29] to discern how a hands-on active learning (HAL) approach influences student education. We suggest how success of the project in a Nigerian case study is creating opportunities for other regional institutions and other developing countries, and we look at course grades and GPAs, and analyze faculty interviews to do an assessment on the overall impact the HAL introduction has had on the students and the chemical engineering program.
2.0 Materials and Methods

2.1 Equipment Description

The DLMs (Figure 1(a)) are mobile and were designed at Washington State University (WSU) by a team composed of co-authors Golter, Van Wie, and WSU College of Engineering & Architecture Machine Shop personnel and an undergraduate student; the system design was reported in an earlier manuscript [30]. They do not require external hookups and have only a 14.8-inch x 12 inch footprint. A sealed lead-acid battery powers a pair of small pumps as well as the pressure transducers, thermocouples and read-out electronics. Two four-liter water tanks are built into the DLM footprint, to allow for hot and cold water use. Two DC motorized 8.3W centrifugal pumps (Rouchon Industries, Inc., Swiftech™, Signal Hill, CA) are situated underneath the DLM below the tanks while system flows are controlled in the 0-40 GPH range by adjustable needle valves on rotameters (King Instrument Company, Garden Grove, CA) located on the system on-off control panel. Type K thermocouples are built into the header where the modular cartridges snap in. Differential pressure transducers (Omega Engineering Inc., Stamford, CT) are also built into each module for the measurement of equipment pressure drop. Analog signals from the Type K thermocouple and Omega Engineering PX26-015DV pressure sensor are pre-amplified with a Burr Brown INA126 instrumentation amplifier (gain=148). The analog signals are made available from the DLM through a standard 9 pin DSUB. These signals are connected to a Measurement Computing USB-1608FS device. Version 5.1 Instical Software (Norton, MA) is used to transform the electric signals into temperature or pressure readouts according to the pre-calibrations. Stream data are then transferred to disk for data storage. Values of the variables are also presented to students through a cell phone display on the front panel of the DLM. The digi-
tal display returns a rounded value of the temperature reading, making the precision of each measurement ± 0.05°C.

A modular design for cartridges that snap into the DLM provides the flexibility to include several unit processes without having to increase the device footprint. The current cartridge options include three heat exchangers, a conventional shell and tube, double pipe and extended area radiator and three fluid mechanics systems, orifice and Venturi meters, and a packed/ fluidized bed.

In many cases, for example the shell and tube heat exchanger shown inserted in the DLM in Figure 1(a), the design is based on standard rules of thumb for heat exchanger design, i.e. window cut, baffle and tube spacing, etc., to construct a functional design. Figure 1(b) displays the cartridge design for a Swiftech™ extended area radiator system used in cooling computer CPUs (Rouchon Industries, Inc., Signal Hill CA) along with an 80 mm fan (Zalman Tech. Co., Korea) – the unit is the subject of the DLM study presented in this paper. Figure 1(c) shows the DLM/HAL classroom at ABU during Van Wie’s Fulbright exchange with the ~1.2 foot cube DLM surrounded by a student team. Co-author Abdul interacts with one group front and center, while Van Wie is barely visible in the back interacting with a group that has returned to their seats while other groups appear in various places around the room assessing their data and comparing values they obtain from models they derive to represent the process being studied. To assess the DLM cartridge approach to steady state, on-line data collection is performed to record temperature data at 32 Hz which is then processed in Excel software using a moving 32-point average to report a data point every seconds.
2.2 Pedagogy implementation

The HAL pedagogy was introduced into CHEN 302, Physical Transport Phenomena II: Heat Transport within the Chemical Engineering Department at Ahmadu Bello University. Prior to the implementation of HAL, the students were briefed by the professor on the objectives and mechanics of the HAL. The topics to be covered in class during the HAL exercises were already contained in the departmental brochure which every student had and included the analysis of a double pipe, shell and tube, and extended area heat exchangers. They were also asked to endorse ABU administration approved forms consenting to the use of the data for publication purposes. The class objectives or learning outcomes for each cartridge implementation would read something like: “By the end of these set of activities the student should understand the concept of hydraulic radius and wetted perimeter amongst other related concepts and also be able to analyze and design an extended area heat exchanger”
Figure 1. The DLM: (a) the DLM with a detachable shell and tube heat exchanger inserted; (b) the extended heat exchanger cartridge used in this study; and (c) a Nigerian HAL classroom with DLMs.
The hands-on active learning employed in this class was particularly labor intensive and logistically involved. The professor handed out reading assignments and take-home quiz (the internet was erratic so e-mailing it to students would not be effective) to all the students on the topic to be covered two days prior to class. Some of the take-home quiz questions, in particular for the extended area heat exchanger, are:

- Under what conditions is it necessary to use an extended area heat exchanger rather than another one we have studied?
- When designing a cooling fin what important factors will affect fin efficiency? Use equation 15.19 from McCabe [31] to explain how these factors affect fin efficiency.

When HAL was implemented, the method of convenient sampling was used to assign the 127 students into two fairly intellectually balanced groups A and B using their previous cumulative grade point average (GPA) as the convenient sorting criteria. Each group was further subdivided into subgroups of 6 students, with an equal mix of “strong”, “average” and “weak” students. This was done to facilitate “balance” between groups with regard to benefits derived from intra subgroup discussions during class and also for the purpose of group homework. We also note that even though the groups were initially numerically symmetrical, some asymmetry was introduced during the implementation by some students not showing up during their assigned activities. However, all 127 students completed the class.

For HAL a guided-inquiry type worksheet covering major concepts and the experimental procedure was developed by the professor and handed out in class. This worksheet contains the professor’s thought provoking questions that are geared towards stimulating students’ intellectual curiosity [32]. Four DLMs were set up on the platform in front of the class. Four student groups came up to the four DLMs simultaneously, interacted with the equipment (with the assistance of
the instructors) over a period of about 10 min where they took measurements of water inlet and outlet temperatures as a function of flow rate and went back to their seats where they continued with discussions on the worksheet. Meanwhile, the other groups kept busy discussing the conceptual and procedural questions on the worksheets as they awaited their turn with the equipment. The professor and the instructor(s) moved between the groups listening to the students, referring them to relevant text sections and tutoring as they circulated around. At certain points the professor stopped the group discussions to give 10-15-minute mini lectures to correct some misconceptions, for example on the concept of hydraulic radius, noted during discussions with students.

Paraphrased worksheet questions, e.g., for the extended area heat exchanger, appear below:

- Use an energy balance and your data to determine the mass flow rate of air
- Use this mass flow rate and the geometry of your exchanger to determine the air Nusselt number
- Determine the air side heat transfer coefficient
- Determine the heat transfer rate using the model in your text and compare to what you obtained experimentally.

2.3 Comparison with Control Group

Late in the semester a controlled study was devised to compare HAL with straight lecture. The class was split roughly in half with 58 in lecture control Group A and 69 in HAL Group B. These were further sub-divided into 6-person teams (i.e. there were a maximum of 6 persons in any group). In this instance the HAL group studied an extended area heat exchanger, not seen in class previously, and in the lecture format the same material was covered. During the lecture the students filled in a worksheet identical to that used during the HAL experience (minus the physi-
cal data), but of course no hands-on equipment was present in the class for visualization of the miniaturized equipment. Exposure to the worksheet for the lecture students assured that both groups had a fair and equal chance of acquiring the same information. However, we view this as an “enhanced” lecture because there were some active discussions interspersed within the lecture format, and the worksheet itself may bias results as the students were given a pre-quiz that would alert them to stay focused on basic principles that would be covered in the lecture and worksheet. The lecture group later used the DLM (next day), but only took the same physical data as the other group and answered the related questions because they already had a lecture on the same topic. This was done to ensure that no student missed or felt like they missed the benefits from the full pedagogy. This could also give stronger weight to positive comments about the two methods as some students could not only compare lecture versus hands-on when topics differed, but could also contrast the approaches for the same topic.

2.4 Assessment Instruments

Multiple-Choice Concept Questions (MCQs): The MCQ set used is a six-question test designed to assess students’ understanding of concepts related to extended-area heat transfer. The test covered basic theory as well as derived equations of performance parameters. The multiple-choice method was adopted because it allows for assessment of factual and evaluative understanding of the subject. It also provides comparison and evaluation of related ideas, concepts, or theories and allows ease of administration to a large number of students. The response choices to each test question were comprised of a key (correct answer) and the distracters designed to capture common student misconceptions of the subject. The designers have identified these common misconceptions over the course of their careers as faculty. The same basic test was given before and after the learning experience. However, measures were taken to ensure that student scores
were kept from being influenced by factors other than ability, such as discussion within a group about which particular lettered answer was correct for a given question. To achieve this, two sets of questions were prepared and administered. One set differed from the other by a rearrangement of the sequence of questions and response choices for each question. We acknowledge the existence of a widely acclaimed and peer reviewed thermal and transport sciences concept inventory [33] which we note is generic and have found useful in our other related studies on course implementation [34-35]. However, because the questions in this validated inventory were not aligned with the DLM hardware and associated activities, we felt compelled to create an appropriate concept question list following some of the rules postulated by Zhao [36] such as the options should be equally likely to a lay person and the number of options should be at least four. The questions were reviewed by a panel of 5 lecturers with between 3-27 years of teaching experience and were found to adequately test what was covered in this particular topic. The results of these two experiments were then collated and analyzed to assess uniformity of performance on the pre-test between the HAL and Lecture groups, and relative amount of improvement. Figure 2 contains a sample concept question used in our study.
The *hydraulic diameter* for the air duct is the:

a) Ratio of fluid volume to total surface area,
\[
\frac{H \cdot 2L_{\text{fin}}}{2(H + 2L_{\text{fin}})} \cdot \frac{W_{\text{fin}}}{W_{\text{fin}}}
\]

b) Root mean side length, \(\sqrt{H \cdot 2L_{\text{fin}}}\)

c) Effective diameter for a pipe with the same cross sectional area,
\[
\sqrt{\frac{4(H \cdot 2L_{\text{fin}})}{\pi}}
\]

d) Ratio of circumference to cross sectional area,
\[
\frac{2(H + 2L_{\text{fin}})}{H \cdot 2L_{\text{fin}}}
\]

**Figure 2:** Options and diagram for one of the multiple-choice questions used in the study.

**Flashlight Survey:** The shortcoming of most exam types of assessment is that they help faculty identify only what students know and what they don’t know. That information is valuable for both formative and summative assessments and for determining the efficacy of an innovation such as the HAL project. However, even concept-based exams do not reveal how students are learning the material. In addition, exams do not easily provide insights that can help improve student learning. A survey was developed to assess HAL with excerpts from the Flashlight Evaluation Handbook [29] and was designed to address the student learning strategy benefit or deficit and receptivity compared to the traditional lecture format in ways that might inform the implementation of the bundled innovation. Specifically, the survey is based on Chickering and Gamson’s [28] “7 PGPs,” principles well vetted in educational research and broadly recognized for their construct validity, practicality, and their subsequent utility for improving teaching and learning practice.
A total of 25 questions were selected from a list of those typically used to assess the Seven Principles and framed in five-point Likert scale [37-38] to address issues such as how much the HAL method enhances team work, student grasp of concepts, and physical visualization of industrial processes. Examples of question wording appear below:

How strongly do you agree with the following statements about this course?

a) Hands on activities helped me understand the course concepts;

b) I was encouraged to answer my own questions.

Compared to other courses to what extent do you:

a) Spend more time on tasks for this class;

b) Discuss topics of the course outside of class;

For purposes of analysis in this paper the seven principles are assigned numbers as follows: 1) faculty-student contact, 2) student-student contact, 3) active learning, 4) prompt feedback, 5) time on task, 6) faculty’s high expectations, and finally, 7) recognition of students’ diverse approaches to learning. A separate section was provided for written responses with the heading “Other Comments” and screened for statements that would buttress the general findings from the collective trends observed in the Likert responses. Clearly the survey not only embodies the research in how people learn, but represents the core values underpinning the HAL pedagogy.

Student grades: While there are many factors that can impact classroom performance, one of the co-authors (Olaofe), who was the ABU Chemical Engineering Exam Officer who recorded all the grades for the Department, noticed a remarkable improvement in the performance of the students who were exposed to Van Wie’s implementation of the group learning pedagogy. Furthermore, he noticed a corresponding change in student behavior i.e. many more group meetings out-
side the classroom. Therefore, to further investigate the efficacy of the new pedagogy, student grades were compared for the present course, CHEN 302, versus a previous lecture only course, CHEN 301, along with GPAs before and after the course. For this we compared the present test set of students (n = 127) to a control set (n = 39), which did not experience the new pedagogy in any way. Paired t-tests were done on the overall student grades before and after the course of study and the first and second semester GPAs to check for any significant improvement from the repeated treatment within each group. To further check for significance of gains between the two groups, a classical two-sample homoscedastic (equal statistical variances, usually for repeated treatments where each treatment has an equal number of samples) t-test was done on the groups. The t-test helps to determine if the average represents the same population or not. Finally, an effect size evaluation was done to gauge the practical significance of the results. The assumptions of data normality and homoscedasticity were checked before applications of these classical tests of significance [39].

Faculty interviews: Six (6) ABU faculty members were interviewed by telephone to gauge their perceptions on how the new pedagogy has affected teaching and learning. Three of them were involved in teaching or grading CHEN 301 and CHEN 302 and the other three were ABU Chemical Engineering Department faculty who were familiar with what we were doing and who, by virtue of their departmental responsibilities, have a good perception of student behaviors and performance. They were asked to consider changes in student-student interaction, and if observing the new pedagogy had influenced their own classroom teaching. We were especially looking for information that would corroborate the findings in the flashlight survey, and especially what was observed in grade improvements as so many factors could explain the phenomena.
3.0 Results and Discussion

3.1 Equipment Performance

There are important technical questions to answer about DLM performance to determine its suitability in addressing learning barriers particularly in developing nations: 1) can a given heat exchange cartridge, in our case the extended area heat exchanger, produce measurable temperature changes when cooling ~50°C (122°F) water with ambient air in equatorial countries, where there is no air conditioning in the classrooms, and inside temperatures can be as high as 30°C (86°F). Will the system reach a quasi-steady state operation quick enough so that a large number of student groups can rotate through a DLM station and have a hands-on learning opportunity? This is important given the typical 100-300 student class sizes, even in courses within a major, and the limited number of DLMs that can be used in a single classroom because of budget and space limitations; 3) Given the DLM hot water reservoir volume of 4 L how long can we sustain a temperature that’s higher than ambient before reservoir contents need to be replaced? This is especially important since electrical power is erratic and one has to consider heating the backup supply of hot water perhaps with the use of a gasoline-powered generator as a power source; and 4) Are there anomalies in the system that make for good engineering learning experiences. The following is a summary of pertinent findings on the DLM-radiator cartridge performance that is also characteristic of what is observed for the double pipe and shell and tube heat exchangers:

- Quasi steady state is reached after 6, 16 and 24 seconds for water flows of 20, 10 and 5 GPH. As expected these are all within the residence time for the flow through the radiator volume, but it also says there is not a large heat sink in the system that prolongs the approach to steady state.

- Changing the flow rate gives a new quasi steady state in a very short time (~ 15 sec).
• Because of rapidity of approach to steady state our experience showed a 6-person student team could become acquainted with a DLM and acquire a set of data within 5-10 min. This allowed all 127 students, in 21 teams, to rotate through the DLM stations in our 2-hour class period.

• Starting at 63°C, it takes about 1 hour for the temperature to drop to a point that is within 1°C of ambient temperature where it is necessary to either recharge the tank with hot water or reheat the energy-depleted water with an immersion heater.

3.2 Student Performance comparing HAL and Lecture Groups

Concept Tests Results. In our HAL vs. Lecture study the ANOVA plot below shows the average scores on a six-question test and mean improvements appears in Figure 4 for the Lecture (A) and HAL (B) groups. Four ANOVA Tests were applied to the data to check for significance as summarized in Table 1. The Confidence Interval plot visually displays the results of the tests where a clear break between two points indicates a significant difference and an overlap between two points indicates no significant difference for the tested populations. Table 1 provides the statistical results of the four tests.
Figure 3: Analysis of variance (ANOVA) plot for the Lecture (A) vs. HAL (B) study on the extended area heat exchanger material. The average raw scores and average difference for both groups in the pre and posttests show mean improvements with substantial overlap in 95% confidence intervals.

Table 1: Summary of ANOVA results.

| ANOVA Test               | $F$ statistic | p-value | $F_{0.95}$  
<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>Mean scores before class</td>
<td>0.01</td>
<td>0.924</td>
<td>3.92</td>
</tr>
<tr>
<td>Group A improvement</td>
<td>139</td>
<td>0.000</td>
<td>3.91</td>
</tr>
<tr>
<td>Group B improvement</td>
<td>75.5</td>
<td>0.000</td>
<td>3.92</td>
</tr>
<tr>
<td>Mean improvements</td>
<td>2.22</td>
<td>0.139</td>
<td>3.92</td>
</tr>
</tbody>
</table>

Tabulated values taken from Perry's Chemical Engineer's Handbook, 1983

The four ANOVA tests provide the basis for a quantitative understanding of HAL in teaching students. There is no significant difference in the pre-lecture/HAL Concept tests performance between Groups A (Lecture) and B (HAL) as expected. This suggests that the students in both
groups had about the same preconceptions. From the ANOVA and Confidence Interval plot above, one can see a clear improvement for both groups. For Group A and Group B, improvements from an original mean score of 2.5 to final mean score of 4.9 and 2.5 to 4.5, respectively, are seen out of a total score of 6, respectively. Finally, a fourth ANOVA on the mean improvements between Group A and B shows there is no significant difference between the performances on the CQ and thus we can say that the HAL and lecture groups had about the same grasp of the extended area heat exchange concepts. This strongly counters the objection raised by faculty attending at every institution and every seminar given by co-author Van Wie on active learning, that students will not learn the material well when learning from each other in a discussion-oriented fashion as opposed to just listening to a lecturer who has significant expertise in the field. It is particularly important to point this out to international faculty where the use of lecture is a strongly entrenched tradition. However, the statistically insignificant improvement of the HAL group is worthy of comment because it was expected that the HAL group would significantly outperform the lecture group as noted by Prince’s review [40] which shows that active learning works but there is a need for careful metrics to gauge the degree to which it does. Prince also pointed out that assessment of active learning is difficult because it usually affects more than one learning outcome and therefore should be assessed using mixed methods, a notion also supported by Adams et al [41]. He also suggests that interpretation of the results should be carefully done to avoid misinterpretation and over interpretation in view of the learning objectives. Based on some of these considerations, the anomaly (although statistically insignificant) in the HAL-Lecture results could be attributed to a misalignment of the assessment tool (the MCQs) with the hands-on activity [34] or some other inadequacy in the design and interpretation of the MCQ [36]. We suggest also that since the lecture itself was active (the HAL and lecture groups
differed mostly in the in-class DLM experiment) and the same concepts were discussed by both
groups with the instructors leading in both cases, the same reading assignments, take home quiz
and worksheets (with an additional data table for the HAL group) were given to both groups dur-
ing the class, the 5-minute MCQs may have been inadequate for testing any intergroup differ-
ence and the close similarity in treatment of both groups could mask any differences. Also, 5
minutes is not enough time to test a difference in analytical/problem solving skills between the
two groups. We further posit the possibility that there exists an inadequacy in the design and in-
terpretation of the MCQ especially regarding the number of questions which is below the mini-
mum of 8 recommended by Zhao to mitigate the effect of guesswork [36]. Golter et al. [35]
have also highlighted the inadequacies of traditional control studies in education research and
proposed a more rigorous experimental model with less emphasis on quantitative studies. This
model is centered on a project-based approach with design discussions reviewed for critical rea-
soning by students and faculty within the experimental site institution and industrial representa-
tives outside the institution. Of course, delivering the course content is not the only objective in
teaching. In fact, the Flashlight Survey will show that the HAL method helps the students to de-
velop some useful skills and has better receptivity than the lecture. In future, we plan to report on
project-driven learning with the DLMs as support equipment and use of a critical reasoning as-
essment instrument used to measure various associated learning outcomes.

Flashlight Survey. There was an excellent survey response rate (116 of the 127 students (93.5%)
who participated in the study turned in their surveys). While no student responded to every
question, all of them responded to between 80 and 90% of the questions. While the 7 PGP s were
woven throughout the 25 questions and six categories, for purpose of analysis the response as-
essment was realigned with the Seven Principles. We note that some of the questions align with
more than one principle in which case we chose the principle with the closest alignment based on
consensus agreement between four of the co-authors all with considerable experience in peda-
gogy assessment. Figure 4 presents analyses of questions based on the PGPs. Only response av-
ergages are shown for each principle to avoid clutter. However, response results on specific ques-
tions are woven into the discussion in the form of percentages.

Figure 4a presents a result for faculty-student contact, PGP1. Regarding PGP1, 76% said they
were likely (42% much more and 34% somewhat more) compared to other courses to discuss
ideas and concepts with the instructor and only 8% said less likely. A striking 84% were more
likely to ask for clarification (55% very likely, 29% likely), and counter to the culture of unques-
tioned respect for authority in Nigeria we found that 65% (28% much more and 37% somewhat
more) felt more comfortable disagreeing with something the instructor said while 10% were less
comfortable. Further insight into PGP1 was gained from student responses on whether they felt
more isolated with the new DLM pedagogy. About 65% of the students responded they felt
‘much less’ (46%) or “somewhat less” (19%) isolated. This question served as a good control
against students simply rushing to fill in the left-most dot, and generally more desirable respons-
es, on the survey sheet because in this case the more desirable responses, of ‘less’ and ‘much
less’ likely, were on the right-most side. The ‘Other Comments’ section contained strong state-
ments in support of the argument that students are more motivated to learn in a setting that pro-
motes student-faculty contact. For example, a student commented that the new DLM pedagogy
“should be extended to other courses taught within the department as it encourages the lecturer-
student relationship”.

Regarding PGP2 (Fig. 4b), 90% of the students (56% much more and 34% somewhat more) said
they were more likely to interact with other students. Only 4% were less likely to interact with
other colleagues. Similar responses were given on questions about discussions inside and outside of the classroom (78% more likely, 14% less likely, and 8% same), and improved collaboration with peers (82% more likely, 9% less likely, and 9% same). The collective responses on questions related to PGP1 and PGP2 suggest that the students recognize that effective learning is collaborative and social not competitive and isolated and that this has been encouraged by the new pedagogy. Furthermore, in analogy to the various types of physical transport phenomena, we posit that the driving force for knowledge transfer from faculty to students is the considerable knowledge and experiential gap between them. However, a lack of deliberate and engineered mutual contact and interaction can indeed retard this transport rate. We submit that the new pedagogy and the DLM have been recognized by students as considerably reducing this impedance.

In line with PGP3 and PGP4 Figures 4c & d focus on active learning and prompt feedback. An overwhelming 87% agreed (50% ‘strongly agree’ and 37% ‘agree’) that hands-on helped more than lecture. Only 6% disagreed (5% ‘disagree’ and 1% ‘strongly disagree’). When asked if hands-on made them better able to visualize ideas, a significant 94% (67% ‘strongly agree’ and 27% ‘agree’) responded in the affirmative. This position was reinforced by a student who said:

“All in all I enjoy the practical method of learning (better) than lecturing”. Another student said, “I personally would like the hands-on learning to be employed in all chemical engineering courses. It really helps to visualize what I’m being taught and think myself; instead of being fed all the knowledge and forced to swallow” Yet another student remarked: “This method helps to visualize processes and gives a better understanding of concepts given in the textbooks”. This statement appears to conflict with the Concept test results (Figure 4), which indicate that there is no significant difference in conceptual gains between the HAL and lecture groups. It is noteworthy however that the Flashlight Survey was administered at the end of the semester after all the
students had been exposed to hands-on learning and lecture at some point. Thus this position may reflect more on the superior sensory perception and retention offered by a combined aural, visual and tactile experience compared to just an aural one [18].

Because the HAL design had in-built hands-on activities (PGP3, active learning), students had little option but to work together in class as they were instructed to come forward to observe DLM processes group-by-group and they were asked to complete in-class worksheets as a group. Whenever it was noticed that several students were sitting by themselves, they were asked to join with their group while at the same time their group was encouraged to receive them. Nevertheless, the question remains on whether the general nature of working together persisted outside of class and whether it was carried over to work in other classes. To answer this we can look at the response results for two questions. First, on whether students were more likely as a result of the hands-on active experience to discuss topics outside of class we find 78% said they were ‘very likely’ (39%) or ‘likely’ (39%) to do so. Secondly, when asked if they were more likely to work on assignments with other students we find 82% said they were ‘very likely’ (49%) or ‘likely’ (33%) to do so. Responses to other questions, such as whether HAL encouraged students to answer their own questions, realize connections between different areas, are more comfortable in discussions, or are pushed to think independently, show the same overwhelmingly positive skew.

Further evidence to support the assertion that the HAL experience was transformative would hopefully be found in looking at class performance and the impact the experience has had on other coursework – preliminary performance indicators will be discussed in the next section.

Concerning whether the in-class activities caused them to miss comments made during a discussion about ideas and concepts taught, there was a more uniform response across the scale with 20% checking ‘very likely’, 17% ‘likely’, 28% unsure, 25% ‘unlikely’, and 11% ‘very unlikely’.
Still we view this latter trend as positive considering that the students were much more inclined to ask for clarification, which encourages feedback from the instructor (PGP4). Furthermore, literature shows that the scenario with the standard lecture is far worse as after the first 50 minutes of lecture retention levels are only at about 20%, that is 80% of the material is effectively missed by students after this point [42]. Concerning whether they were likely to give suggestions or complaints, about 60% responded in the affirmative. This again is in line with PGP4, which encourages a two-way feedback that generally serves as a precursor to system improvements.
Figure 4. A depiction of the flashlight survey responses on the indicators for the Seven Principles for Good Practice in Undergraduate Education [28].
Figures 4e, f & g show some responses to questions that combine the last three principles. Regarding PGP5 (time on task), 88% (47% ‘much more’ and 31% ‘somewhat more’) were likely to spend more time to learn new material than before. This reflects good practice which posits that time and energy are necessary for learning. Only 14% said they were unlikely to spend more time on task. Regarding PGP6 (high expectations), 89% (68% ‘much more’ and 21% ‘somewhat more’) felt they were more prepared for the engineering field; 95% agree (65% ‘strongly agree’ and 30% ‘agree’) they are better able to grasp facts; 89% (63% ‘strongly agree’ and 26% ‘agree’) agree they gain a more thorough understanding of the ideas which coincides with the 84% (45% ‘much more’ and 36% ‘more’) that indicate they had to create their own understanding of the information to be learned. All these align with high expectations for students by faculty. Regarding PGP7, which recognizes diversity, 89% feel they are more likely (61% ‘much more’ and 28% ‘somewhat more’) to learn in new ways. Another 85% (39% strongly agree and 46% agree) agree they have a higher tendency to consider contrasting points of view because of the new pedagogy. This suggests that the students have a better appreciation of the diverse ways of viewing a problem and, through this, are learning more from their colleagues and are thus better prepared for teamwork.

When asked if they were satisfied with the introduction of hands-on group learning, survey results are quite positive with 95% responding they were either ‘very satisfied’ (51%) or ‘satisfied’ (44%) with the pedagogy. Only 3% indicated they were ‘unsatisfied’. We note that one question leaves us with some uncertainty, however. When asked if the learning technique is overrated, 46% (20% ‘strongly agree’ and 26% ‘agree’) replied in the affirmative, 17% are ‘unsure’, 18% ‘disagree’ and 15% ‘strongly disagree. Further evidence to support the fact that some students had concerns or would like modifications to the approach is suggested by a student who wrote
"A special class should be separately organize (d) to take care of the hands-on rather than using (the) normal lecture hour". This may be because students are yet to become totally comfortable with the new teaching method. Still the mixed responses to the "overrated" question are surprising given the overall satisfaction expressed. This leads us to wonder if the question was misunderstood and we plan to add a phrase in future surveys that says “… overrated and I would prefer the standard lecture or some other teaching approach”. We will follow this immediately with a request like “If you agree that the technique is overrated, please state your reason why and offer suggestions on how to improve the approach.” We also posit that this could be in line with the “high expectations” principle of good practice as the students could have grasped all that was offered in this introductory exposure and are therefore yearning for an enhanced experience. We aim to pursue this line of argument and to modify the pedagogy to accommodate more challenging concepts. Further inferences drawn from the other comments section of the survey are as follows: out of a random sample of 50 students, 15 suggested that this approach be extended to other courses, 13 were of the opinion that the HAL has helped them to be more appreciative of teamwork, 15 said it enhanced their grasp of key concepts and also helped them to relate theory and practice. Another 4 of the respondents were of the opinion that more time should be allotted to the HAL class, 1 person suggested that a special class outside normal classes should be created for it, and 2 respondents said they preferred the normal lecture format to the HAL.

In addition to the preceding analyses, the students were observed to use some terminologies in their everyday conversation, the context of which exhibited their grasp of the fundamental ideas of the subject. Below is a sample of the comments (in "pidgin", a common local language in Nigeria):
“Prof transfer coefficient high today o!” [The student is excited that the Prof’s “knowledge transfer coefficient” is high].

“Old boy I don reach steady state for today, I dey go sleep...” [The student has had all the studying he can handle for the day and compares his state to the concept of steady state].

Overall, the reception to the DLMs and hands-on active learning approach has been quite encouraging. As students are exposed more to this new method, the authors have no doubt they will continue to find it stimulating and useful in their learning.

3.3 Interviews with ABU faculty

Faculty interviews corroborate the survey results showing classroom organization and instructor interactions and experiences occurred with the implementation that strongly promoted the 7 PGPs. In addition, they give credence to the enhanced scores in CHEN 302 over 301 and GPA improvements for the test group when compared to the control group as will be described in the next section. More importantly there’s evidence the new pedagogy is having a transformative effect on the other faculty as a whole, and finally the interviews reveal some important concerns about the DLM system that should be addressed to improve on HAL efficacy.

Regarding the observation of evidence for the 7 Principles we highlight the following comments:

• One of the interviewees implies that the pedagogy gets the faculty more engaged with the students and comments, “(there are) strengths both for the teacher and the students”. PGP1: faculty-student contact.

• One faculty said, “They have better teamwork skills”; another said, “I see students studying in groups.” This lecturer “attributes it” i.e. to the new HAL approach; others said: “I noticed that students are very much at home in a group study environment and they learn so much from it... If you give a lecture some students will understand one part more than others... by
the time they interact with each other they are now able to combine the knowledge into a whole”. PGP2: student-student contact.

• “Prior to Dr. Van Wie, we are not used to the modules... It is commendable that now students in the department have this opportunity. It is really very good for them and I think they are really excited.” Another said, “When I was a student I had problems translating what the teacher says into practical visualization... but now you are able to see pressure in very practical terms... It was very thrilling... I really enjoyed his approach”… “I saw students coming together trying to solve problems, trying to explain things to one another a couple of months after Professor Van Wie had started teaching them”. Finally, another said, “(to) visualize (is) better than imagination... I strongly believe this approach is the best”. PGP3: active learning.

• Others infer that the implementation has heightened faculty expectations (PGP6) especially as it applies to group work, “I now see students working in groups in the classroom ... in the departmental library...” or “Sometimes I’ll be passing by at night and ... discovered ... students studying in groups.”

• “(The) strength of group study is the tremendous speed with which things get done. When you have people from different backgrounds working together, they look at problems from different perspectives”. PGP7: recognition of students’ diverse approaches to learning.

It is well established that group activities, projects and homework sessions leads to enhanced classroom performance [43], and retention [44], and can lead to a spread effect that stimulates enhanced performance in other classes [45]. When one sees the definitive increase in overall student performance (cited below in the section on “Impact of the new pedagogy ...” one must admit there can be many factors that could affect performance in any specific class and overall per-
formance in the breadth of classes taken by a student in any semester. However, during the time of the HAL implementation there is strong commentary evidence from other ABU faculty of an immediate and transformative shift toward group activities. Hence, the positive Flashlight surveys and improved performance in CHEN 302 and overall GPA (see next section) for the test group is consistent with the literature reports. Supportive faculty comments include:

- “I now see students working in groups in the classroom close to my office and in the departmental library…”
- “Sometimes I’ll be passing by at night and I will think a lecture was going on but then I discovered it was just students studying in groups.”
- “I saw students coming together trying to solve problems, trying to explain things to one another a couple of months after Professor Van Wie had started teaching them”.

The following comments illustrate that the HAL implementation, though it only occurred in two classes over the course of Van Wie’s Fulbright exchange, was transformative for the Chemical Engineering faculty at ABU and that a philosophical shift has taken place, as emphasis on altered pedagogical approaches is becoming ingrained throughout the curriculum:

- “Lecturers are now giving more group work to students. I see more group work in the department but not necessarily on the DLMS…
- “The approach has challenged faculty to go back and learn how to teach with DLMs.”
- “Particularly the equipment he brought. I got attracted to them because I had already started seeing things in that way…when I was a student I had problems translating what the teacher says into practical visualization… but now you are able to see pressure in very practical terms… It was very thrilling… I really enjoyed his approach”
• “I used a variant of Prof Van Wie’s hands-on to teach Bernoulli equation using different bank note denominations to represent the different terms in the Bernoulli equation”.

• When asked “Do you think you would use group work in your classes?” one lecturer responded with “Definitely I will. I may even say I have started it with what Dr. Van Wie introduced...” ... “When students see things practically they are better able to view things and comprehend and follow and make contributions”.

• Regarding whether he used group work or study another responded with “Yes I do. ... CHEN 301 ..., which I taught with two of my colleagues. We used the hands-on equipment to teach the students. We taught the students orally and also allowed them to have hands-on experience themselves.”

The faculty members also expressed healthy concerns about the alternative pedagogy, concerns which are likely to help them beware of the potential pitfalls and implementation barriers to active, group and hands-on activities. For example, two of them pointed out the need for proper training and support materials; specifically a senior faculty who used the DLMs in his class complained that: “...most lecturers are not properly trained in the pedagogy, there were no facilities to repair them (the DLMs) and there was no operations manual...” While draft copies of the operations manual were subsequently made available, the interviewee brings up a good point that ample training and exposure to operations procedures is important. When done properly with a guided step-by-step DLM operating procedure we find students and lecturers have a learning curve of about 10 min after which use of DLMs in subsequent classes, even with use of alternate cartridges, does not require more than 1-2 min of further instruction. Also, since the time of implementation, training of technicians on trouble shooting the DLMs has been conducted.
Also, a World Bank-sponsored collaborative research project between WSU and Ahmadu Bello University (ABU), Nigeria is in progress to develop and disseminate the DLMs, workbooks and pedagogy to all major universities with chemical engineering programs in Nigeria. Another major issue identified is that of plagiarism. This can be exacerbated in the group setting especially in the large classrooms that typically exist in developing nations and where the average students can take 20 credits or more. Van Wie himself notes a student commented to him that if he gives too much homework it just encourages them to copy and when he first introduced the group work in the classroom found he spent considerable time one period collecting electrical engineering homework that was being copied by students for another class. He notes however, that had he not been circulating during the group time he would not have noticed and would not have been able to correct the problem. Others addressed the tendency that group work has in tempting plagiarism and offered other solutions to keep in mind when implementing a HAL approach. For example, one said: “There’s less tendency for plagiarism when the group is well blended. Only unserious students indulge in plagiarism.” Another proffered this solution: “To avoid plagiarism, we ask them to do presentations and ask them questions randomly and we can thus identify the slackers…”

3.4 Impact of the new pedagogy on overall student performance.

Because of the enthusiasm with which the DLM/HAL pedagogy was received, we expected students’ performance would improve in the CHEN 302 class at hand over that of the pre-requisite CHEN 301. Moreover if the groups were truly effective we might expect a carryover effect where the mentality would persist in a way that group study, at least on homework and projects, would continue in other classes taken by the same students and that this might improve their average performance as evidenced in GPA. The presence of a transformative group mindset was
confirmed through the faculty interviews (above) where they report they saw an increase in the number and frequency of student study groups after the introduction of the new pedagogy and that they were encouraged to include active and hands-on elements in their classes.

Figure 5a shows the final class percentages for individual students in the study group in CHEN 302 where HAL was introduced to those having the pre-requisite CHEN 301 which did not employ HAL. Final class percentages for a comparison group from the immediate previous year when neither CHEN 302 nor 301 used HAL are shown in Figure 5b. A similar comparison for the GPAs in the second semester when the new pedagogy was introduced to the semester before for the study group is shown in Figure 5c; similar results for the same control group are shown in Fig 5d. It can be observed that for the majority of students in the test group, the final class scores for CHEN 302 and the second semester GPAs were generally higher than for the first semester when the new pedagogy had not been introduced. On the other hand, the control does not show similar improvement but rather we notice that only a few of the final class scores improved and the GPAs appear stagnant on average.

Table 2 is a summary of the statistical analysis that was done on the class scores and GPAs to check for significant differences between the groups. For the test and control groups there is a statistically significant difference in CHEN 301 and 302 scores within each population [columns 2 and 3] and that difference is toward the positive for the test group and by roughly the same amount toward the negative for the control group as evidenced by the t-statistic for the difference between groups. The effect size is 18%, which according to Cohen’s $d$ 20% guideline shows at best small practical significance; however, we must also consider ABU grading criteria. For the test group there is an improvement of 13% from a mean grade of 45% (D) to 51% (C), while for the control group there is a 21% decrease from 56% (C) to 44% (E). The letter grades of C, D
and E correspond to course GPA contributions of 3, 2 and 1, respectively on a 5-point scale and hence the effect size is substantial when viewed in this light.

Table 2: Summary of t-test results at 5% risk level.

<table>
<thead>
<tr>
<th>Hypothesized mean dif.</th>
<th>Test Group Class Scores</th>
<th>Control Group Class Scores</th>
<th>Change in Scores; Test vs. Control</th>
<th>Test Group GPA</th>
<th>Control Group GPA</th>
<th>Change in GPA Test vs. Control</th>
</tr>
</thead>
<tbody>
<tr>
<td>t statistic</td>
<td>6.59</td>
<td>6.84</td>
<td>10.0</td>
<td>16.3</td>
<td>0.043</td>
<td>8.22</td>
</tr>
<tr>
<td>t critical [one-tail]</td>
<td>1.66</td>
<td>1.68</td>
<td>1.66</td>
<td>1.66</td>
<td>1.69</td>
<td>1.65</td>
</tr>
<tr>
<td>t critical [two-tail]</td>
<td>1.99</td>
<td>2.01</td>
<td>1.98</td>
<td>2.02</td>
<td>1.98</td>
<td></td>
</tr>
<tr>
<td>Effect size</td>
<td>0.048</td>
<td>0.076</td>
<td>0.181</td>
<td>0.874</td>
<td>0.003</td>
<td>2.43</td>
</tr>
<tr>
<td>Practically significant difference?</td>
<td>No, effect size &lt; 20%</td>
<td>No, effect size &lt; 20%</td>
<td>Small, effect size ~ 20%</td>
<td>Yes, Large effect</td>
<td>No, effect size &lt; 20%</td>
<td>Yes, very large effect</td>
</tr>
</tbody>
</table>

The change in semester GPA from first to second semester within the control group (column 4) was found to be statistically and practically insignificant. This suggests, on the average, a situation of class stasis. In sharp contrast, the practical significance of the improvement within the test group is very large. Figures 5c&d offer strong pictorial reinforcement of these contrasting scenarios. In fact there is a computed 243% practical significance in GPA improvements between the two populations (see Table 2, column 7) which amounts to better than 80% non-overlap between the two populations. We suggest the implementation of the new pedagogy in CHEN 302, which hinges on the 7 PGPs [3, 28], resulted in a spread effect to other classes. One could intimate that the overall semester GPA improvement within the population resulted from carryover of a team spirit to other coursework that included better peer interaction, faculty-student interac-
tion, and higher inquisitiveness of the students. We aim to pursue this angle in further batches of students to confirm trends and probable causality.

**Figure 5:** Scatter plots for course scores (a) experimental and (b) control; and GPA (c) experimental and (d) control.

While this preliminary data along with faculty observations are encouraging we must insert some strong qualifying remarks. It is difficult to say that the improvements that coincided with the HAL implementation were solely due to HAL. Perhaps there were other factors influencing the students in prior years such as turmoil at the university or perhaps an analysis of other student
populations will reveal random variations of similar magnitudes as those observed for the HAL semester. Nevertheless, the trends are consistent with what is seen in the literature. For example, Crouch et al. [7] have shown that when students talk to each other they translate information into language they understand and that this is not always true when they hear the material from an expert. Even when an expert performs in-class demonstrations, students still learn less than when they discuss the demonstration themselves. Also, Pauk [46] shows that students who study together do better: “Friends learning a subject together often share the same difficulties and can thus enlighten one another very effectively”. It is precisely these kinds of student-to-student activities that were brought up in the faculty interviews, and this is in sharp contrast to the competitive environment that has typically existed where students were known to even hide textbooks from each other.

3.5 Assessments by DLM/HAL Adopters

The implementation of the new HAL/DLM pedagogy in ABU by co-author Van Wie during his Fulbright exchange is a radical shift from what most ABU lecturers are used to. The assessment by the Nigerian co-authors in terms of how the new pedagogy can help solve educational problems in Nigeria is enlightening. Of course, use of the approach will also have similar implications throughout Africa as well as other developing nations. Following are our conclusions:

**Exposure to Industrial Equipment:** Most Nigerian students are not exposed to industrial equipment operations to the same extent as their counterparts in more developed nations as the students lack the same opportunities to go on paid industrial internships (a consequence of African industrial underdevelopment) and the universities often do not have the budgets to buy and/or maintain larger scale unit operations laboratory equipment. Hence, the Miniaturized DLM helps bridge this gap.
Practicality: The portability of the DLMs when compared to traditional laboratory equipment enhances easy movement from class to class and the small size makes them easy to use in the limited class space encountered in most African classrooms. This design allows DLMs to be placed on most classroom desk surfaces without resulting in tripping hazards from power cords or water hoses being run to or from the module. We also note that because the DLM reaches steady state quickly it creates a particular advantage for the introduction of HAL when using a small number of units for large 100-300-student Nigerian classrooms given the associated time constraints encountered in passing so many groups through the DLM learning stations.

Versatility: The DLM is versatile due to the availability of a wide spectrum of plug-in cartridges and therefore, when commercially available, the DLM is expected to be significantly cheaper than conventional laboratory equipment. The DLM with 6 plug-in cartridges viz: shell & tube, double pipe, and extended area heat exchangers; Venturi and orifice meters; and packed/fluidized beds, and accessories are expected to cost about $8,000 when commercialized. This is much cheaper than currently available commercial bench scale equipment which just for a heat transfer bench, heat exchanger, and data acquisition system currently used at ABU can cost as much as $25,000 - $30,000. The maintenance is expected to be a function of usage with an upper estimate of 5% of usage time. The parts are very durable and it is expected that a new electronics package will alleviate problems we have had with solder joints and will also be readily replaceable as an entire unit.

Given the cost one could ask why not replace the hands-on aspect with a video or a single-team demonstration followed by sharing of results. The authors feel this may not be ideal considering the experiential, hands-on nature of most engineering functions. Perhaps an extreme example
would be to suggest a hungry student watch a cartoon of someone eating a burger with the hope that the said student’s hunger will be assuaged. Moreover, we acknowledge the work of Crouch et al. [7] mentioned earlier that shows demonstrations are only effective when students actively participate in them. In this study aptly titled “Classroom demonstrations: Learning tools or entertainment?, the authors found that learning is enhanced by increasing students’ engagement and that students who predict the demonstration before seeing it display significantly better understanding.

**Suitability for Lengthy Class Periods:** The average student is weary of the traditional lecture format where the lecturer reads out theory upon “abstract” theory with the result that “half” the students are drowsy halfway through a lecture that in Nigeria typically takes 2 – 3 hours. The extended lectures given once per week rather than every other day is important for the limited number of faculty available as many of them are conducting research for higher degrees at other locations where research equipment is more available. In addition there is a short supply of PhDs so universities hire short term lecturers from other universities to come in and teach short courses. Conversely, the HAL method stimulates the students’ curiosity and holds their attention even over the prolonged classroom periods.

**Student Accountability – Staying on Task:** Because lecturers circulate, interacting with groups during a HAL implementation, the students are motivated to participate rather than work on other assignments unrelated to the class [47]. This problem is inherent in the Nigerian system – students are typically required to take 22 – 25 credits per semester, in contrast to U.S. practices where the credit numbers typically range from 15 – 18; because of the large number of credits students find it more challenging to find time to do their homework and therefore use class time to do so. We find that despite the underlying temptation to use class time for other purposes, with
HAL the students are enthused about the subject at hand and do not want to miss out on the excitement of working together.

Facilitates group work: Group activities in the educational curriculum of most developing nations, especially Nigeria, is somewhat restricted. Until recently the norm has been a rather narrow and individualistic mode of learning where every student works independently for the most part. In fact this deplorable situation gave rise to the so called ‘OYO’ (‘On Your Own’) syndrome where every student learns his own way with the attendant individual misconceptions and limited learning. However, in view of the current global trend where engineering designs are a result of team projects, a paradigm shift is necessary for developing nations if they are to become globally relevant. The construction of the DLM and in fact almost any piece of engineering laboratory equipment is such that one individual cannot operate and record observations simultaneously, and much less do so quickly. In fact, because the DLM reaches steady state so rapidly this alone creates the necessity for a team approach. Furthermore, the new pedagogy incorporates all the PGP’s including group work.

More comprehensive learning experience: The practical aspects of visualizing, touching, hearing and hand manipulation of pilot scale industrial processes have all been until now relegated to a separate laboratory experience. Furthermore, while current educational methods focus on individuals learning a narrow set of concepts, real world industrial problems are complex and solutions to these problems requires that engineers and scientists work in broad multi-talented teams. Hence, one would expect to see aspects of active [3, 48-52], problem-based [53] and cooperative learning [54-56] in such courses. Science and engineering education in other nations, especially developing ones, are therefore in need of incorporating these new and better pedagogies to train
the current generation of students. This is in contrast to institutions such as WSU where the DLMs have previously been implemented [30]. Furthermore, DLMs foster the use of a more tactile or sensing learning environment, and reinforce the learning of “soft skills”, such as teamwork, interdependence and mutual accountability desired for a successful engineering career. Student groups can make observations, collect data and have a discussion about the system, as well as models and calculations that describe the system.

We concede that cognitive gains due solely to the equipment have not yet been confirmed by the CI instrument, but assert that gains in the affective domain which may well serve as motivation for cognitive gain can be readily inferred from the survey data. We plan to pursue thorough assessment of cognitive gains from using the DLM and the pedagogy, employing better controls so as to clearly elucidate and delineate gains in a higher/or different outcomes domain that is attributable to the equipment alone. We would assess how the DLM can promote skills acquisition and also how it can help students whose learning skills are skewed towards the visual and tactile. Also, we observe that averages, as have been used in reporting the cognitive gains, only give insight into what is happening in a general population and may mask the cognitive gains for individual students whose learning style is in sync with the equipment. To confirm or refute this we plan to study outcomes for individual students in future studies.

**Mitigating the lack of utilities:** Because of the prevalent, even daily electricity outages and lack of running water to most buildings in Nigeria and indeed other developing nations, the built-in battery and fluid reservoirs of the DLMs are very useful. Run time for the batteries exceeds the two hours of normal classroom time in Nigeria and the rapid approach to steady state (as was illustrated in the equipment performance section) allows the rotating of groups of students through DLM stations – a group can easily obtain data within 5 – 10 min, and several groups can
use the same piece of equipment long before battery storage is depleted and before hot and cold water reservoirs equilibrate. The author notes an instance during installment and testing of a current commercial-brand bench-scale heat exchange experimental device in the Chemical Engineering laboratory at ABU; the installer had to stop because there was a sudden power outage. Meanwhile Prof. Van Wie’s son, a Fine Arts major who accompanied him on the Fulbright, performed a similar experiment on the DLM and did not experience such a problem and finished an entire afternoon of experiments while the aforementioned technician was still waiting for power to be restored.

**Enhancements:** While the authors believe that the pedagogy as it stands is a good innovation, we would like to state that there is still room for improvement. In line with this WSU recently introduced a project-driven pedagogy using the DLMs as supporting equipment [35]. The targeted outcomes in this project-based class are Bloom taxonomy objectives such as analytical, problem solving, synthesis and group skills. The assessments being used in this alternative approach include critical thinking and group process rubrics, and problem solving and synthesis ratings. We suspect that the problem solving assessments would be a good way to evaluate the efficacy of the DLMs especially if the solutions require knowledge gained by a practical hands-on experience.

**4.0 Conclusions**

The new DLMs are getting a warm reception and showing suitability for use in the Heat Transport course in the Chemical Engineering Department at Ahmadu Bello University, Zaria, Nigeria. The system’s onboard battery and hot and cool water reservoirs make it useful in infrastructural challenged environments. A technical analysis of the DLM shows a quasi-steady state temperature can be achieved in at most 24 sec at the lowest water flow rate (5 GPH) used in this study. We also estimated that a minimum of 48 students from 12 groups can have useful quality
learning on a DLM over a one hour period (half the standard class duration). This is important in view of the typically large classes encountered in Nigerian universities. Also, the DLM’s simplicity obviates a long learning curve, and the attendant frustration that may cause students, so that groups can pass through the DLM hands-on learning station quickly and with ease.

HAL pedagogy when used simultaneously with the DLMs has positively impacted the learning experience of students. A two-way ANOVA shows the students improved conceptually by the same amount in both a lecture and a HAL setting. This suggests that replacing a conventional lecture with a hands-on active environment does not hinder learning that some may argue can only come through a lecture by a highly qualified instructor.

One could argue that the insignificant difference in gains in conceptual understanding between the HAL and Lecture appears to obviate the need for extra investment in the teaching equipment. However, we note that the Flashlight survey results make a strong case for use of the HAL / DLM pedagogy especially in how it has helped promote development of certain “professional skills” like team work, grasp of important facts, and persistence of concepts, visualization of ideas, peer interaction and curiosity. An overwhelming 96% were of the opinion that they are better able to remember important facts, while 88% agree they have a more thorough understanding of ideas and concepts, and 94% said they are better able to visualize ideas. Further analysis of the survey in terms of the 7 PGPs, upon which the survey is based, shows strong supportive evidence, with responses in the 80+% range, that the HAL / DLM pedagogy is highly effective in stimulating all Seven Practices. HAL has also provided the students with new and varied ways of self learning and group learning which are in tandem with world-class best practice.

Survey responses of ABU Chemical Engineering faculty not only show the new approach was well received, but corroborate the persistence of a group learning mentality among the students.
that extends to other coursework. Furthermore, there appears to be a cultural shift in teaching and learning philosophy among the faculty to the extent they now often include hands-on and active exercises in their respective classes.

The CHEN 302 and GPA improvement for the set of students who were exposed to the new HAL pedagogy over a previous set who were not is intriguing especially as the Flashlight and faculty surveys corroborate a systemic shift and spread effect toward team learning. However compelling this observation may be, we note that it could have just been fortuitous and therefore we plan to pursue this line of thinking to establish reproducibility and causality.

When taking collectively the positive Flashlight survey data, equal gains in conceptual understanding between Lecture and HAL/DLM use, development of other skills required in future practice, faculty enthusiasm, and apparent spread effect, the new HAL/DLM pedagogy is very attractive for use in classrooms of developing nations, especially when considering the relatively low cost and practicality of the DLMs. We intend to investigate conceptual aspects further by checking the suitability and alignment of our MCQ test to the hands-on aspect of the whole pedagogy package. We also intend to look into other more robust assessment tools, for instance the worksheets and a Critical Thinking Rubric designed at WSU that could be in better alignment with the DLM.

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Engineering Process Transport Phenomena Implemented while Using Hands-on Desktop Units”; the Staff and Students of the Department of Chemical Engineering, Ahmadu Bello University, Zaria, Nigeria, as well as the Staff of Voiland School of Chemical and Bioengineering at WSU and the Centre for Teaching Learning and Technology, now renamed the Office of Assessment and Innovation, at WSU. Besides interview comments made by co-authors O.O Olaofe, F.O Anafi and E.G. Shide we particularly acknowledge the helpful interview comments made by ABU Chemical Engineering Department faculty including those made by T.K. Bello, Prof. S.S. Adefila, and O.A Ajayi.
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CHAPTER THREE

A Tale of Two Pedagogies – Comparing Lecture and Active Learning in a Fluids and Heat Transfer Class

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Abstract

Various configurations of pedagogies of engagement have been touted as facilitating better learning outcomes than traditional lecture. However, many studies in the extant literature have not articulated exactly what elements of learning outcomes these pedagogies have addressed and how exactly implementation should be structured to satisfy learner position
on the trajectory of knowing. Faculty adoption, pedagogy deployment and student receptivity issues can also not be overlooked. This paper therefore presents a study in a lecture-based class where infusions of a new pedagogy dubbed CHAPL (Cooperative Hands-on Active Problem-based Learning) were successfully negotiated. We report the design of the learning experience and assessment, and outcomes of the study. Some topics were taught using traditional lecture while some were taught using a mix of lecture and the new pedagogy. The results show no statistical difference in cognitive learning outcomes between the two approaches based on exam performance but significant differences in student-reported perspectives and affective outcomes. These outcomes and lessons learned are discussed with a view to informing future learning experience and assessment design, and implementation.

**Keywords:** cooperative, hands-on, active, and problem-based learning (CHAPL), cognitive outcomes, affective outcomes.
I. Introduction

The community of engineering educators has been stridently calling for alternative pedagogies to replace or at least supplement the traditional lecture in educating engineers of the present and future. This call has been necessitated by engineering education stakeholders concerns about the quality of engineering graduates [1-4] and their inadequacies in meeting the challenges of a complex and constantly evolving workplace. One of the important stakeholders, the university accreditation body ABET, listed some criteria for important learning outcomes [5-7]. Criterion 3 of the so-called EC2000 ABET criteria includes the following general learning outcomes (p. 171 of [6]):

- **a)** An ability to apply **knowledge** of mathematics, science, and engineering;
- **b)** An ability to design and conduct experiments, as well as to analyze and interpret data;
- **c)** An ability to design a system, component, or process to meet desired needs;
- **d)** An ability to function on multidisciplinary **teams**;
- **e)** An ability to identify, formulate, and solve engineering problems;
- **f)** A recognition of the need for, and an ability to engage in, lifelong learning;

Engineering faculty have taken note of ABET and other stakeholder expectations and there is increasing consensus among faculty that pedagogies of engagement are the way to go in helping students develop these competencies [8-10]. These new pedagogies have been reported by various workers to engender better student learning gains in the cognitive, affective and/or psychomotor domains when compared to straight lecture [11-21]. A meta-analysis conducted by Dochy and colleagues in 43 real-life classrooms (mostly medical) [22] showed that students who
learned in problem-based learning (PBL) environments show better knowledge application outcomes than students who learned with lecture. Another meta-analysis carried out by the same authors from an assessment perspective [23] shows that PBL students perform better in understanding of the principles that link concepts and the linking of concepts and principles while lecture students perform better in understanding of concepts. Even though some of the studies report extra-anecdotal evidence of cognitive gains [17], few have been robust enough to capture the broader vista of cognition (for instance, knowledge, application and integration) in one study. In many instances, the student’s cognition was captured using a single representative score [11, 12, 19, 24-26]. Yadav and colleagues’ comparison of case study and lecture in two mechanical engineering topics shows no difference in conceptual knowledge using a single concept question score [11]. Springer, Stanne and Donovan’s meta-analysis [25] of small-group learning in Science Technology Engineering and Mathematics (STEM) disciplines reports that 40 field studies assessed cognition with instructor-crafted exams (mostly concept tests) while 13 used standard tests and found higher cognitive outcomes in the PBL group. Moreover, objectivity could not be ascertained in all of these studies due to lack of detailed description of the assessment instrument and type of tasks. Bowen’s [26] meta-analyses of high school and college students’ chemistry cognition (via concept tests) in cooperative classes also reports gains over traditional delivery. Prince’s meta-analyses [12] of active learning experiments reports that these learning interventions show gains over traditional lecture (effect sizes >0.5) but cautions on the localization limitations of educational studies. Mantri and colleagues [20] report relatively higher mean scores for PBL over lecture students in a digital electronics knowledge and skills test. Hake’s [13] and Redish’s [27] studies are two which stand out for their use of more than one measure to quantify cognition. Hake’s study involving more than six thousand students finds
significant normalized gains in conceptual understanding using the Force Concept Inventory (FCI) developed by Hestenes and Halloun [28] and understanding through application using the quantitative Hestenes-Wells [29] Mechanics Baseline Test (MBT). Redish report learning gains for computer-based active-engagement tutorials over traditional tutorials using FCI as a test of foundational knowledge and a free-response question as a test of application of principles.

In summary, the aforementioned studies report cognitive gains of engaging learning experiences over traditional passive lectures even though objectivity limitations cannot be overruled in many of them. Also, many of the studies report one measure of cognition using a single assessment artifact. Many other studies which measured more than one cognitive outcome did so with multiple assessment artifacts.

In this paper we report on a comparison of processes and learning outcomes between topics taught by interactive lecture and topics presented via Cooperative Hands-on Active Problem-based Learning (CHAPL) interspersed with brief just-in-time lectures. Our primary hypothesis is that there will be significant differences in cognitive outcomes and student receptivity (affective outcomes) for the topics experienced through lecture and those experienced through CHAPL.

The processes and assessment artifacts in both lecture and CHAPL approaches are described with a view to highlighting the differences and implications for learning experience and assessment design. Assessment artifacts in the form of final examination questions for the lecture and CHAPL topics were rated by the professor teaching the class. A survey designed based on Fink’s cognitive and affective outcomes [30] and Principles of Good Practice (PGP) in undergraduate education [31] was thereafter administered to gauge students’ feelings and perceptions about CHAPL vis-à-vis lecture. Regarding Fink’s taxonomy the survey has more of a focus on students’ perceptions of what aspect of cognition, foundational knowledge,
application or integration, is most enhanced by the pedagogies implemented, with some questions targeting the affective domain as well. We believe this approach will have far-reaching formative implications in engineering education and assessment design.

II. A brief description of pedagogies of engagement

Various configurations of the so-called pedagogies of engagement have been proposed, tested and found to engender better learning outcomes than traditional passive lecture with little or no interaction [32]. Some of the more prominent pedagogies of engagement are [8, 12, 15]:

**Cooperative learning:** This is a learning strategy where small groups of learners work together to maximize individual and group learning. Each individual in a group has responsibility for facilitating group learning for a particular set of concepts. It involves positive interdependence, group and individual accountability.

**Collaborative learning:** This approach to learning is similar to cooperative learning but generally requires an individual take responsibility for a larger segment of a project and does not involve carefully structured individual accountability.

**Problem/Project-based Learning (PBL):** This is a type of learning that results from the process of working towards the solution to a given problem or the completion of a larger scale project which can be seen as containing multiple components of individual smaller problems.

**Interactive Lectures:** This is a kind of lecture where the students and instructor interact more than in traditional passive lectures [31] [32]http://www.jstor.org/stable/10.2307/2943844. In this mode, students are asked questions and are allowed to ask questions of the instructor. For
example, the think-pair-share protocol and also brief discussion of concepts or issues are used in this mode.

III. Methodology

This section details the tools and procedures used in this study. It contains descriptions of participants, learning experience design, assessment design, and implementation.

Participants in the study (participant profile):

Twenty-nine (29) chemical engineering junior students enrolled at a research university in the Pacific North West (PNW) participated in this study. They consisted of six (6) females and twenty-three (23) males. Participants’ previous cumulative grade point average (CGPA) ranged from 2.29 to 4.0 with 55% of the students having a CGPA above 3.0. All the participants had fulfilled the prerequisites to this class which are: Chemical Engineering major, Chemical Principles and Calculations (ChE 201), and Introduction to Transport Processes (ChE 310). The second prerequisite focuses on “fundamental concepts of chemical engineering; problem-solving techniques and applications in stoichiometry, material and energy balances, and phase equilibria”, while the third focuses on “fundamentals of the phenomena governing the transport of momentum, energy, and mass” [33].

Classroom design (design of study environment)

The class in this study, ChE 332, dubbed Fluid Mechanics and Heat Transfer (FMHT) is a junior level two-credit course which deals with “design calculations, operation and evaluation equipment used in fluid flow, heat transfer, and evaporation” [33]. It is offered every spring semester at the Washington State University where this study was conducted. For the new
pedagogy which involves elements of group study, the twenty nine students were divided up into seven groups of three and two groups of four using a convenient sampling procedure. In this sampling procedure, the students were grouped so that each group contained an equitable mix of higher and lower GPAs. There was also an attempt to address diversity by distributing women and international students among teams usually in pairs so as not to isolate a single underrepresented person. However to foster autonomy (p. 75-76 of ref [34]), students were allowed to choose one person they would prefer to work with. Schedules for each student were also taken into consideration to avoid clashes and thus facilitate smoother group work. Meeting times as specified in the College of Engineering time table was 8:10-9:00am Tuesdays and Thursdays.

An overview of procedure

In this study, “equivalent” pairs of topics taught using the different approaches, lecture and the new CHAPL pedagogy , were used as control and intervention, respectively. The dependent variables here are examination scores for lecture and CHAPL cum lecture questions (i.e. CHAPL topic questions that contain minimal elements of a lecture topic) and the responses to the survey based on Fink’s taxonomy of significant learning [30] and Principles of Good Practice in undergraduate education. An instance of a CHAPL cum lecture examination question is one which deals with heat exchange between two streams in a 158-tube, 1-1 shell and tube heat exchanger because even though shell & tube heat exchanger was a CHAPL topic, the question contains cognitive elements from the double pipe heat exchanger topic which was covered in a lecture format.
Table 1: List of equivalent topics and the order of presentation (in parentheses).

<table>
<thead>
<tr>
<th>Serial #</th>
<th>Lecture topic</th>
<th>Equivalent CHAPL topic</th>
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<tr>
<td>1</td>
<td>Pressure drop with fittings (second)</td>
<td>Reynolds experiment (first)</td>
</tr>
<tr>
<td>2</td>
<td>Pitot tube (first)</td>
<td>Venturi and orifice (second)</td>
</tr>
<tr>
<td>3</td>
<td>Packed bed (first)</td>
<td>Fluidized bed (second)</td>
</tr>
<tr>
<td>4</td>
<td>Double pipe heat exchanger (first)</td>
<td>Shell &amp; tube heat exchanger (second)</td>
</tr>
<tr>
<td>5</td>
<td>Pool Boiling (second)</td>
<td>Evaporative cooler (first)</td>
</tr>
</tbody>
</table>

A list of the equivalencies in this work is presented in Table 1. Each “equivalent” pair of topics was chosen based on similarity of content, concepts, principles, and complexity of processes contained in each topic. This approach is markedly different from other studies where: (1) randomized control experimental designs used to compare a new intervention to a traditional one use “control” and “experimental” participants [35-38], (2) baseline data replaces the control group and a single experimental or intervention group is used to ensure more efficient classroom learning as the instructor would not need to repeat activities with any of the groups and no student misses out on benefits of the new learning intervention [39], (3) in situations where the use of baseline data is inappropriate, for instance when the learning objectives and assessment methodologies of the baseline and experiment are different and when there are significant external factors like different instructors, “triangulation” (that is, using other types of data, for instance surveys to support the interpretation of the primary data) is used to mitigate the influence of such external factors [40]. Such an experimental design where topic-pairs within the domain of Fluid Mechanics on one hand, and Heat Transfer on the other, rather than participants
or baseline data are used as experiment and control respectively represents a better alternative to baseline data.

**Learning activities**

The learning activities in the class were designed based on the principles of backward design [41] and guided inquiry. The desired learning outcomes were first established, acceptable evidence of the achievement of these outcomes was then determined and learning activities were built around these. The learning objectives for the class were outlined in the syllabus posted on the course website prior to the commencement of learning activities. A typical statement of learning objectives is the following:

After completing the fifth week you should be able to:

a) Calculate the drag coefficient for a solid particle in a fluid stream.

b) Define and calculate the Reynolds number for a solid particle in a fluid stream.

c) Calculate the pressure drop of a fluid flowing through a bed of stationary solid particles.

d) Describe why a bubble rising through a fluid has a different drag coefficient than a solid particle of the same diameter settling in a fluid.

e) Describe the different types of typical packing for absorbers.

f) Explain why flooding occurs and the impact of both gas and liquid velocities on flooding.

g) Calculate the pressure drop in a packed tower for gas/liquid contacting.
h) Calculate the pressure drop in a fluidized bed and explain why it is constant with flow rate.

i) Explain why a fluidized bed expands and calculate the bed expansion as a function of superficial velocity.

j) Explain why a $\Delta P$ vs. $v$ curve may have a hysteresis effect when decreasing $v$ as opposed to increasing $v$.

**Implementation of the lecture section**

The lectures were designed and implemented by Professor 1. His lecture style, even though teacher-centered, involved some modicum of participation in the form of within-lecture questions thrown to the student audience to elicit student reflection and responses on the topic at hand. In a lecture typical of this professor, he starts with a model like the mechanical energy equation, explains all the terms and relates the equation to real systems that the students can easily identify with. In one instance where he was explaining dynamics of packed beds, he passed around different types of industrial packing as a visual reinforcement of the lecture. He usually brought the lecture to a close by assigning a textbook problem as homework.

**Description of the Desktop Learning Modules (DLMs)**

The miniature industrial process equipment otherwise called Desktop Learning Modules (DLMs) are small desktop-scale replica of some common equipment used in industrial processing involving fluid flow and heat transfer. They consist of a base unit containing tanks, rechargeable battery, pipes and pumps to which a detachable cartridge of the equipment can be inserted via the
DLM plug-in. These DLMs or older versions of the same have been used in previous studies in various contexts by our group [42-44].

Figure 1 shows the base unit of the DLM. On the front of the base unit and above the insertion point of the cartridge are located two cell phone display read-outs for differential pressure and stream temperatures, respectively. The rotameter for controlling flow rate from the pumps is located at the lower left hand corner. The base units and cartridges were designed with portability, ease of use, versatility and safety in mind. To these ends they are small and compact, have their own tanks and plumbing, and are battery-driven to prevent tripping hazards that could occur if they had electrical cords.

Figure 1. The DLM base unit showing its different features.

The plug-in cartridges are miniaturized equipment that can be conveniently inserted into the base unit to form the complete DLM. Figure 2 shows the cartridges employed in this study. The venturi, orifice and packed/fluidized bed cartridges were used to study the design and analyses of fluid flow equipment while the shell & tube, evaporative cooling and extended area cartridges were used to study the design and analyses of heat exchange equipment.
Figure 2: Some of the plug-in cartridges: (a) venturi (b) orifice (c) shell & tube heat exchanger (d) packed/fluidized bed and (e) evaporative cooler, each of which can be installed interchangeably on the DLM base unit shown in figure 1.

Implementation of the CHAPL section

Elements of the CHAPL pedagogy were implemented by a second professor (Professor 2) in some of the FM&HT topics to provide a learner-centered learning experience. The CHAPL pedagogy was developed by one of the co-authors on this paper at the institution where this study was done [45] and includes the following: 1) Reading Assignments, 2) Take-home quizzes based on the reading assignments, 3) Concept quizzes assembled from a variety of sources, 4) Group dynamics, 5) In-class experiments with miniature industrial process equipment or DLMs designed at the institution where the study took place [43], 6) Specially designed worksheets which further increase student engagement in student learning, 7) Jigsaw cooperative teams in which the students are involved in designing some learning activities, 8) Presentations on an
authentic problem or project. Elements of the full pedagogy to be implemented in this class were selected based on negotiations between the two professors. Accordingly, 4, 5, 6 and 7 were chosen. Also, topics for implementing the CHAPL were agreed upon by the two professors (see Table 1 above). It is noteworthy to mention that positive assessment results from previous implementations of CHAPL [46, 47] were instrumental in convincing the lecture professor to adopt elements of this new pedagogy. This is in line with the extant literature on assessment results as a driver for pedagogical innovation adoption [48].

During CHAPL classes, students worked in their assigned groups on short experiments (the hands-on part) and worksheets based on these experiments after a brief 5-minute introduction. The instructor and/or the TA went around coaching them, listening to their discussions on the content of the worksheets and providing necessary prompts to aid cognition. The following represent typical scaffolding prompts:

“Have you considered taking the definition of the hydraulic radius from your text and applying it to the tubes through which liquid flows in the extended area heat exchanger?”

"Have you read the section where the Grashoff number is introduced to account for enhanced heat transfer due to natural convection?”

Often when common misconceptions were detected among the groups, the professor halted the activities and gave a short mini-lecture (5 – 10 min) to correct the misconceptions. An instance of this would be when the instructor on perceiving a pervasive misconception in students’ understanding of the effective diameter of a fin, interrupted group activities, went to the board and explained that the effective diameter needed for calculations is determined based on looking
at the fin as a heat conduit from the wall outward and that one calculates the effective diameter based on a hydraulic radius for a cross-section perpendicular to the heat flow.

For the “jigsaw” or cooperative learning part [45, 49], one student from each group was drawn to contribute to a two-class period think-tank exercise on designing learning experiences for one of three pieces of miniature industrial process equipment. Their design would be based on worksheets developed during past implementation of the DLM and CHAPL exercises. Each student now returned to his/her home group having become an “expert” on that particular topic to conduct his/her group members through the learning experience using the worksheet as a guide. A video clip showing elements of the CHAPL (introduction to the activities, student-instructor interactions, student-student interactions, student-DLM interaction and mini lecture) can be accessed via the link: http://vimeo.com/32990202.

Survey administration

Because exams alone do not provide adequate insights into how students perceive a pedagogical intervention is helping them to learn the material in a domain, surveys have become necessary [50]. In mixed methods research surveys provide further data [24, 40, 51] in answering research questions. However, the survey questions need to be carefully worded in order not to be misconstrued as the research question itself while at the same time preserving respondent comprehensibility. This will enhance validity as well as response interpretation.

Youn et al. [24] in a mixed methods educational research framed the following main research question:
“Will a pre-instructional e-learning strategy help engineering students cognitively and affectively prepare for their classroom learning?”

They employed the following prompts to answer this question:

“After completing this self-paced program, how prepared do you feel to listen to the classroom lecture on this module?

Not prepared at all 1 2 3 4 5 Very well prepared”

“Will this self-paced program help you to increase your confidence in understanding the classroom lecture?

Will not help at all 1 2 3 4 5 Will help very much”

Confidential surveys allow students to give unfettered feedback about their learning experience with the pedagogy and also give suggestions on improvements. In this survey, which was designed and administered on the university’s web-based “Skylight” survey system, the students were asked to respond to two categories of questions. The first category focused on a comparison between this class and traditional lecture classes they have taken or are taking while the second focused on a comparison of the two types of activities in this class (lecture and new pedagogy)

The wording for the first category of questions was: “In contrast to traditional lecture classes I found because of the mix of lecture and the new learning systems (Desktop Learning Module or DLM and allied activities) that I...”

This was followed by further prompts and Likert-type response choices [52] structured as follows:

1. Understand basic principles of (FM) & (HT).
   a. Strongly agree
b. Agree

c. Unsure

d. Disagree

e. Strongly disagree

This question serves to elicit student perception of the inculcation of principles of good practice in undergraduate education in this class [31, 53]. Students were informed at the beginning, verbally and through the IRB approved informed consent form, and reminded throughout the semester that they would be asked to evaluate their experiences with the DLM and lecture at the end of the semester. The intent was to limit memory decay problems often associated with self-report instruments (e.g., surveys) that solicit recall of information after the fact. We did not directly measure the effects of homework assignments, quizzes and tests as there were no survey questions to that effect. Because self-report instruments may be susceptible to social desirability biases, thereby limiting the validity of conclusions that can be drawn from them (Bowman, 2011 [54]), we attempted to minimize this effect by administering the survey anonymously (via the institutional survey website skylight.wsu.edu). Of the 28 students in the class 23 elected to participate in the study by signing IRB forms, all of which responded to the survey.

IV. Results and discussion

In this section we present the cognitive results from the written examinations and also results of the survey. We discuss our findings and highlight important lessons learned.
Examination results

The final examination results are presented and discussed with a view to highlighting the important attributes and implications of this cognitive outcome. Table 2 presents a comparison of performance on examination questions related to lecture topics on one hand and CHAPL cum lecture topics (i.e. questions that we consider contain cognitive elements from CHAPL and lecture topics but with more of an emphasis on CHAPL) on the other. For instance, the topic of double pipe heat exchanger was taught by lecture while the topic of shell & tube was a CHAPL activity. These two topics have significant overlap in cognitive elements and so an exam question on a shell & tube heat exchanger would be considered a CHAPL cum lecture question.

Table 2 Lecture question (Q2) compared with CHAPL+ Lecture questions (Q1, Q3 & Q4) at 5% allowable error rate.

<table>
<thead>
<tr>
<th>Question pair</th>
<th>Mean (%)</th>
<th>Standard deviation (%)</th>
<th>Comparative Statistics</th>
<th>N (No. students)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q2 (Lecture) compared to (Lecture + CHAPL):</td>
<td>63</td>
<td>27</td>
<td>T-statistic: +0.75; T-critical: 1.67; Effect size: +0.21</td>
<td>63</td>
</tr>
<tr>
<td>Q1</td>
<td>68</td>
<td>19</td>
<td>1. No; 2. Small</td>
<td>23</td>
</tr>
<tr>
<td>Q3</td>
<td>54</td>
<td>37</td>
<td>-1.09; 1.67; -0.30</td>
<td>23</td>
</tr>
<tr>
<td>Q4</td>
<td>66</td>
<td>30</td>
<td>+0.5; 1.71; +0.09</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 2 shows the paired t-test results comparing question 2 (a lecture topic question) and questions 1, 3 and 4 (CHAPL-cum lecture topics questions) at a 5% allowable error rate. Overall
the table shows no statistical and little to no practical differences between the performances on the questions. All the questions on the exam require significant system analysis, application of mathematical models and calculations. These require a demonstration of conceptual knowledge and problem solving skills. Question 2 is a question on conduction in a composite material (wall of a house composed of layers of different material). Question 1 deals with pressure drop in a 1-1 shell and tube heat exchanger. Question 3 deals with heat exchange between the heat generated in a nuclear fuel element and water coolant in cross flow. Question 4 deals with heat exchange between two streams in a 158-tube, 1-1 shell and tube exchanger.

A comparison of question 2 with 1 and 4, respectively, indicates there is no positive significant difference in test scores between 2 and 1 on one hand, and 2 and 4 on the other (students did better on 1 and 4 than on 2, even though insignificantly so). The results also show that the students did insignificantly better on question 2 than on 3 (another ‘CHAPL cum Lecture’ related question). Thus we can say that apparently students had at least an equal grasp of the Lecture topic and CHAPL topics. This counters a widely held notion that students will not learn the material well in situations of significant self-directedness as they will from an expert lecturer. Pauk [55] believes learner-directedness can lead to more cognitive gains because students explain principles to each other in a language they can more easily grasp. Felder [56] also lends credence to this view but cautions that the learner-centered pedagogy must be well implemented. He adds that aside from the widely accepted fact that well-implemented learner-centered pedagogies promote better cognitive skills, they also help to retain the students’ attention compared to instructor-centered monologues. However, we note that because of our bias and abundant literature touting CHAPL related pedagogies [8, 10, 12, 18, 57-63] involved in presenting the topics related to questions 1, 3 and 4, it was expected that the students will
achieve significantly better scores on these questions than on 2. Prince [12] in his review has however cautioned about the difficulty inherent in measuring and interpreting learning outcomes of active pedagogies because more than one type of learning outcome is involved and students have different learning styles. This view is also supported by Adams et al. [51] who proposed multiple measures to gauge the efficacy of a learning intervention. In addition, we propose that a lump assessor-assigned number score for each question may not adequately capture the various elements of cognition such as foundational knowledge, application and integration of knowledge [30], and how the pedagogies used in the implementation are influencing the development of these different but related cognitive skills. Therefore, to obtain preliminary data about how the learning interventions in this study affected these three facets of cognition and also the general student receptivity to the innovation, a survey based on Fink’s taxonomy [30] and principles of good practice in undergraduate education [31] was administered and examined.

**Survey Results**

In this section anecdotal data about student’s perceptions of the learning interventions in this study are presented. Among other things, this section presents data showing students’ impressions on how the various learning activities in this class have influenced their learning of the material and therefore preparedness for professional life. Table 3 is a summary of student responses to a broad range of prompts.
Table 3. Comparison of the present class to other lecture classes that the students have experienced.

<table>
<thead>
<tr>
<th>Abbreviated Prompt</th>
<th>Likert responses, % †</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>In contrast to lecture, I found with the mix of lecture &amp; DLM activities that I can better:</strong></td>
<td></td>
</tr>
<tr>
<td>Understand principles of FMHT</td>
<td>Strongly agree 56.5</td>
</tr>
<tr>
<td>Apply principles of FMHT</td>
<td>Agree 60.9</td>
</tr>
<tr>
<td>Integrate principles of FMHT</td>
<td>Unsure 4.3</td>
</tr>
<tr>
<td>Answer my own questions</td>
<td>Disagree 17.4</td>
</tr>
<tr>
<td><strong>Responses on Principles of Good Practice in Undergraduate Education:</strong></td>
<td>Strongly disagree 8.7</td>
</tr>
<tr>
<td>Spend more time on task</td>
<td>Much more 26.1</td>
</tr>
<tr>
<td>Discuss topics outside class</td>
<td>Somewhat more 34.8</td>
</tr>
<tr>
<td>Interchange ideas with other students</td>
<td>The same 17.4</td>
</tr>
<tr>
<td>Learn in new ways</td>
<td>Somewhat less 4.3</td>
</tr>
<tr>
<td>Feel more isolated</td>
<td>Much less 34.8</td>
</tr>
<tr>
<td>Discuss ideas with instructor</td>
<td>13.0</td>
</tr>
<tr>
<td>Use own unique abilities &amp; skills to aid understanding</td>
<td>4.3</td>
</tr>
<tr>
<td>Challenged to create own understanding</td>
<td>39.1</td>
</tr>
<tr>
<td>Feel more prepared for work in the field</td>
<td>21.7</td>
</tr>
<tr>
<td><strong>Responses on Principles of Good Practice in Undergraduate Education:</strong></td>
<td>4.3</td>
</tr>
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</tr>
<tr>
<td>Feel more prepared for work in the field</td>
<td>21.7</td>
</tr>
<tr>
<td>† Largest % in bold</td>
<td></td>
</tr>
</tbody>
</table>

The first three prompts directly address three dimensions of cognition important to FMHT, viz- foundational knowledge, application and integration. The majority (69.5%) of students in this study are positive (13% “strongly agree” and 56.5% “agree”) that the mix of activities in this class when compared to traditional lecture classes they have taken or are taking, appear to help them create better understanding of the foundational principles of the class. This is attributable to the fact that principles from lecture are reinforced by hands-on experiments and group discussions guided by a worksheet. This powerful blend of different learning experiences is
believed to be better than straight lecture [64] because some difficult principles are reinforced right there in the class by the experiments and visual reinforcements (no need to go to the laboratory to find out). Instances of this include observations in the venturi cartridge where in steady flow pressure goes down in the smaller diameter throat region where fluid speeds up, and in the dye injection cartridges where the transition from laminar to turbulent flow is conveniently demonstrated. A further look at the table shows that 4.3% of the students are neutral (unsure) while 26.1% are negative (17.4 “disagree”, 8.4% “strongly disagree”). These disagreements might be tied to different learning styles where we find that some students still adhere to a traditional lecture bias or show a lack of experience in a hands-on active environment and hence initial discomfort with the approach. Alternatively, the version of the DLM used in this implementation had intermittent electronics issues that made obtaining data frustrating for students at times as was noted in end-of-year evaluations. We also found comments to this effect in past implementations where the class was fully based on a CHAPL environment from start to finish.

When prompted on application, 73.9% of the students responded positively (13% “strongly agree” and 60.9% “agree”) that this class helped to apply FMHT principles more than a solely lecture class would have done. This position is attributable to the real-time data from a physical system they could see and analyze, coupled with the worksheet which asks them to compare theoretical predictions to their data. Furthermore, various elements of Fink’s application including critical and practical thinking were more inherent in the CHAPL activities and could have carried over to other problems that were assigned to the students. An instance of practical thinking can be found in the shell & tube activity. Here students were asked to compute the heat lost by the hotter water, compare to the heat gained by the colder water and proffer reasons for,
and means to reduce, this disparity based on the physical system before them. A student whose
heat balance computations indicate that the heat gained by the colder is higher than the heat loss
by the hotter water could surmise instrument error (critical thinking) and may ask for
independent corroboration of temperature measurements using, say, a hand-held digital
thermocouple (creative thinking). Other instances of application thinking prompts abound in the
CHAPL activities and worksheets. This can be contrasted with a lot of text book problems which
are mostly devoid of critical and practical thinking prompts (the text book issue is even more
complicated with the ready availability of solutions manual).

This is believed to lend more authenticity to the learning experience and its assessment [65, 66].

In response to the prompt on integration, 73.9% of the students responded positively (8.7%
“strongly agree” and 65.2% “agree”) that the mix of learning experiences in this class made them
able to integrate ideas better than straight lecture would. This response level may be attributed to
the visual and tactile reinforcement of textbook and lecture integration of fluid mechanics, heat
and mass transfer principles by the activities. Students experienced how fluid mechanics, such as
operation in the turbulent regime, influenced heat transfer in the shell & tube and extended area
heat transfer modules, and also how fluid mechanics and mass transfer influenced heat transfer in
the evaporative cooling module.

The rest of the prompts in this category focused on how the students believed that elements of
good practice in undergraduate education were infused in this class compared to traditional
lecture classes. The prompt “discuss ideas with instructor” is in line with the first principle of
good practice (PGP) in undergraduate education namely faculty-student interaction. In response
to this prompt 47.8% were positive that they had more interactions with the instructor than they
would have had in a traditional lecture, 21.7% perceived the same level of interaction and 30.4% perceived a comparatively reduced level of interaction. These results show that about half of the class perceived and hopefully took advantage of the interactive environment that was created in this class. Of course we have to admit that individual differences also come into play in such a diverse classroom. As in many educational surveys, it is possible that social desirability factors may have contributed to some of the “lesser” responses although the assurance of confidentiality for respondents in our study may have limited this considerably.

The second PGP is reflected in the prompts “interchange ideas with other students” and “discuss topics outside class”. The former prompt yielded a 60.8% positive response, 34.8% indifferent and 4.3% negative response. The higher positive response compared to instructor-student interaction is not surprising considering that peers understand each other’s language and are more comfortable learning together. According to Pauk [55]: “Friends learning a subject together often share the same difficulties and can thus enlighten one another very effectively.”

The prompts: “encouraged to answer own questions” and “use own unique abilities & skills to aid understanding” all reflect the third PGP namely active learning. According to Chickering and Gamson [31], a learner ought to be actively engaged in constructing knowledge and skills rather than passively acquiring it from a lecturer. An equal proportion of respondents (65.2%) reported that they were more likely to feel challenged to create their own understanding and use their unique skills to aid understanding of the subject matter in this class than in traditional lecture classes.

Spending time on worthy tasks is the fourth PGP considered in this work and the prompt to measure this yielded a 60.9% positive response. This indicates that the students are more likely to spend more time studying the material most likely due to an aroused interest and authentic and
challenging tasks that transcend typical text book homework. The following typical (implicit) student comments buttress this point:

“The new learning system definitely makes me more independent. I read [the] textbook a lot and discuss [more] with other students.”

“[Um] we had to look [up] more … on our own instead of asking for help.”

“New learning system require[s] a lot more time to study, but lecture give[s] us the basic understanding (passive learning).”

The fifth PGP considered in this work is termed “high expectations”. The main prompt used to measure this showed that 56.5% of respondents felt more prepared for professional work in the field because of the activities in this class compared to a lecture class. This prompt implies that faculty generally have high expectations of their students (at least they should) and therefore expect them to develop abilities such as creating their own understanding and answering their own questions so they can be better prepared for work in the field. The following student comments imply that the students perceive the instructors expect them to take more responsibility for their own learning:

“The new system made us each responsible for our groups learning. This makes us learn things a lot stronger independently so we can teach others.”

“Yes, taught me better ways to answer my own questions, or at the very least make informed conjecture before seeking help.”

“I think the activities did a good job of teaching us how to apply the equations and principles to a real working system, and to understand how the theoretical models varied compared to the real system. I think understanding this will be useful in preparing us for professional practice.”
Learning in diverse ways was the next PGP considered in this work and positive responses to the prompt “learn in new ways” was 52.1%. This suggests that over half of the students perceive they benefitted from different ideas that members of the group contributed towards solving a particular problem. This is why most engineering firms assign teams to work on projects so as to harness the power of group work while still placing a high premium on individual accountability. However, 17.3% said they were less likely to learn in new ways, while 30.4% were unsure, which when taken in the context of frustrations with DLM reliability (see recommendations below), could suggest such students would be more sure if they consistently had a better experience with the hands-on equipment.

Figure 3 depicts students’ responses to the second category of questions, namely how the two main learning experience types in this class influenced different dimensions of cognition. Figure 3 (a) and (b) show the results for the cognitive dimension, basic or foundational knowledge. The first chart on the left shows that 34.8% of the students agree that CHAPL helped more than lecture to understand basic principles of FMHT as opposed to 56.5% who agree that lecture helped more. These results may be because of the way the CHAPL was configured, where students were led to find out answers to their own questions by themselves as opposed to the lecture where they are provided with information by the “expert” (the professor). Hence, the students perceive that lecture was more helpful in providing them basic information. This position is strengthened by comments made by some students. One student commented: “The lecture and activities were both useful, side by side, in that they let me learn in multiple ways. The lectures did better at teaching the fundamental theories and such. The activities gave me the opportunity to really think about it and better understand the equations and the real use of the theory.” Another student commented: “lecture help more in understanding the basic idea, but
other activities help in applying it”. We also note that a lot more students disagreed, 39.1% (21.7% disagree and 17.4% strongly disagree), that the CHAPL helped in understanding basic principles more than the lecture, which showed only a 17.4% total disagreement. This position is buttressed by a student comment: “Lecture is straight forward and simple. You can compare to the book so that it is easier to study. With the jigsaw and hands on it was harder to get a hold on the ideas. The stuff learned while doing the group work was normally not directly in the book so that I could dissect it.” Another student commented: “From the lectures, I felt like I was guided through problems, and so I knew how to do them later. But in the activities I feel like I was forced to teach everything to myself, and I always felt completely lost when trying to do activity based homework assignments.” These statements suggest that some students are not ready for self-directedness in their learning experience and that more initial guidance is needed before we can expect significant self-directedness. An excerpt from Kirschner, Sweller and Clark’s article in Educational Psychologist [67] puts it more succinctly:

“Although unguided or minimally guided instructional approaches are very popular and intuitively appealing, the point is made that these approaches ignore both the structures that constitute human cognitive architecture and evidence from empirical studies over the past half-century that consistently indicate that minimally guided instruction is less effective and less efficient than instructional approaches that place a strong emphasis on guidance of the student learning process. The advantage of guidance begins to recede only when learners have sufficiently high prior knowledge to provide “internal” guidance.”

We take prior knowledge in this excerpt to mean foundational knowledge and plan to have preparatory lectures before hands-on activities in future implementations of the CHAPL. This is expected to build up students’ knowledge base preparatory to more self-directedness.
Figures 3(c) and (d) suggest that CHAPL was more useful than lecture in helping students develop application skills. A significant 47.8% were positive that the CHAPL was better compared to a 30.4% who thought the lecture was better in building application skills. Although the lecturer has had vast experience in the industry and vividly described relevant processes from his repertoire, we assert that a hands-on experience helps the students more or at least equally. For instance the students were able to physically see why a baffle was needed in a shell and tube heat exchanger and do a thorough analysis of its architecture from the live 3D miniaturized equipment system, analyze an extended area heat exchanger whose design was different from that in the texts, compare experimental to predicted data, see first-hand how real life equipment fails and analyze what could be responsible, among other skills that they will find useful in their professional life. Some student comments help to shed more light on this. One student commented: “I think the activities did a good job of teaching us how to apply the equations and principles to a real working system, and to understand how the theoretical models varied compared to the real system. I think understanding this will be useful in preparing us for professional practice.” Another had this to say: “The only big difference in working with the activities as compared to lecture would be the fact that we have an idea of what some of the systems look like in operation.” Yet another student said: “It gave me experience trouble shooting equipment and gave me a good visual representation of the equipment.” Another said: “Visualization of equipment is a big deal to understand how they work.” These comments lend further credence to the literature that stresses the usefulness of tactile and visual experiences in engineering learning [43, 68-70].
Figure 3: Students’ perceptions of how the two main types of learning interventions in the class under study (“ChE 332”) influenced their learning.

In the final subset, figure 3 (e) and (f), we summarize student responses to the prompt about integration of principles of FMHT. Because many chemical engineering problems of industrial importance are rarely isolated fluid mechanics or heat transfer problems, the importance of integration of knowledge and skills across topics cannot be overemphasized. The authors believe that the students have had adequate exposure to the terms and procedures that imply integration during the lectures and in the worksheets. For instance, the students were instructed they had to
calculate a Reynolds number (Fluid Mechanics) and based on the value they were then to choose the appropriate Nusselt correlation (Heat Transfer). Slightly more students (43.4%) respond that lecture helped them integrate compared to 34.7% who opine that CHAPL is more important for integration of FMHT principles. What is important to understand are, in both cases, those asserting either lecture or CHAPL is better are less than 50% – that indicates neither approach alone is desirable for significant learning with regard to the integration index. However, if one combines the positive responses from the two cases, the total is 78.1% which is consistent with the 73.9% from Table 3 who say the mix of learning approaches is better than traditional lecture alone. This provides strong evidence that the mixed approach is essential for assisting the largest number of students. This is one of the most significant findings in this work as it is consistent with learning styles inventories assessments which show that students within a classroom have different learning styles [71, 72] and in order to reach the broadest cross-section a mix of learning activities is necessary [71].

Figures 4 summarizes student responses on which of the 6 indices within Fink’s taxonomy, the 3 cognitive and the 3 affective dimensions, is impacted most for the 23 respondents when using CHAPL on one hand, and lecture on the other. First, we see figure 4 corroborates students’ views expressed in figure 3 as figure 4a shows 65.2% respond that lecture most impacts basic knowledge of FMHT principles, and 43.5%, representing the largest bar in figure 4b, respond that CHAPL most impacts application of FMHT principles.

What is instructive is further analysis regarding the next most frequent responses. For lecture we see application ranked highest by 13% of the students, caring by 8.7%, followed by integration, becoming an independent learner and other by 4.3%, with no one selecting group work. For
CHAPL becoming an independent learner was ranked highest by 17.4% of the students, followed by integration and other each ranked highest by 13%, basic knowledge by 8.7%, group work appreciation by 4.3% of the students and no one selecting caring about FMHT in everyday life. What is significant here is with CHAPL we see, based on the relative spread of “impacted you most” rankings, greater breadth in terms of Fink’s indices of significant learning as 43.5% selected other Fink’s indices, which is equal to the number selecting the most frequent response of application of FMHT principles, whereas with lecture only 30.5% selected other indices. Also, with CHAPL 1/5th or 21.7% of students rank elements in the affective domain, i.e. independent learning and group work, as being affected most by the approach; by contrast with lecture only 13% selected elements in the affective domain.
Figure 4. Charts depicting areas of most impact by the learning experiences on the students.

It’s important to discuss further the area of appreciation for group work. For the CHAPL approach – at least 1 of 23 students (4.3%) ranked this as most important while for lecture not a
single student ranked appreciation for group work as being most impacted. However, overall the group work aspect seemed to have a positive reception when looking at a question centered specifically on how much they valued group work with 60.9% responding they valued group work “very much” or that it was “indispensable”. Another 30.4% at least say “It’s Ok” totaling 91.3% that recognize group work as being important, while only 8.7% say they do not value group work “very much” or “at all”. The positive responses are buttressed by written comments. One student commented “The group work was useful because it gave me the chance to learn from other students”. Another commented: “Group work gave me other views of ideas”. One student qualified their response saying “Group work is really dependent on what group mates you have”. We note that the students are aware of the indispensability of group skills in professional engineering settings and are therefore grateful for opportunities to build these skills.

Furthermore, with regard to selection of “Becoming a more independent learner” by 17.4% of the respondents, we attribute this to the higher degree of self-directedness built into the CHAPL via the worksheets and reading assignments. We admit however that even though we believe developing independent learning skills in students is a good thing, students were not all happy about the degree of self-directedness in this CHAPL implementation. Some of the comments were favorable while others were not. Some of the positive student comments are reproduced below:

“The activities and group learning did do a better job of teaching me to learn the material independently and figure out things myself.”

“The new system made us each responsible for our groups learning. This makes us learn things a lot stronger independently so we can teach others.”
“Yes, taught me better ways to answer my own questions, or at the very least make informed conjecture before seeking help.”

Other students had mixed feelings about the new learning system or CHAPL and its self-directedness potential:

“I believe that lecture helped make me a more independent learner while the new learning system made me slightly reliant on other peoples input to understand a concept.”

“I was forced to be an independent learner in this course. Period. So, I guess that’s something good about the course and the learning system.”

“I really like the new learning system, but I think the additional readings didn't help much and the book either. I like to learn on my own but it was difficult for me to find more information online with better explanations. I still think a lecture about the module prior to the module would be very helpful.”

“Lecture probably doesn't have enough independent learning, but the new learning system has too much.”

We have noted these comments made regarding independent learning and intend to take them into consideration when making formative decisions for future implementations. For instance we intend to give more in-depth preparatory briefings prior to active learning sessions.

Regarding lecture and the affective dimensions of Fink’s taxonomy, 8.7% of students reported that lecture helped them to care more about FMHT in everyday life while the CHAPL did not. This could be attributed to the lecturer giving the students examples of the manifestations of
FMHT in everyday life in his introductory lecture while CHAPL only focused on some specifics of FMHT in industry using miniaturized industrial equipment as the study aid, but without introducing the utility of such processes. Presenting industrial examples to students without first giving a general talk on everyday examples clearly does not constitute “everyday life” and so we aim to include preparatory mini-lectures that would give more background information to boost student affective gains.

What will be helpful in future studies will be including questions regarding the relative impact on each of Fink’s indices for lecture vs. CHAPL, as well as for the combination of the two approaches during a semester. The results presented here, however, provide strong evidence about the importance and implied synergy in the blending of lecture and CHAPL in learning experience design and implementation as together they provide the broadest set of learning experiences, and especially for foundational knowledge and application.

Summary of student recommendations

Aside from general comments made by the students in response to associated prompts, the students were prompted for recommendations on how to improve the learning experience for future implementations. A summary of their recommendations is given below.

a. Lecture/Pre-lab prior to module activity and worksheets. About 29% (6 out of 21 respondents) believe that a lecture or “pre-lab” prior to the module activity would be beneficial. This resonates with Kirschner and co-workers [67] view that students should be given adequate preparatory knowledge before expecting any self-directedness. A student comment reinforces this view: “Pre-lab time. Having
a single day to explain AND do the exercise results in very low understanding. A day to explain the concepts behind the activity and relevant equations before doing the lab would be much more beneficial”. Another student commented: “I think that these activities would be great IF and ONLY IF, a knowledgeable person (like a TA or a professor) were to take EACH group through the operation of the DLMs, the interpretation of the data recorded, and the concepts (and related equations) regarding the scenario represented by the DLM. One CANNOT expect students to "learn" anything by placing them in front of a module they don't know anything about and asking them to collect data and then interpret it. If they don't know about the system first - they won't know what they're doing or the purpose of the DLM activity.”

b. **Properly functioning equipment.** A significant 38% (8 out of 21 respondents) believe that the malfunctioning equipment was a learning distraction. A typical student comment is: “make The DLM's work better. More than half the time the data received from them resulted in a very large error and confused many of the students. I would also like the jigsaw groups be properly directed by a professor. Because of the lack of time our class had, it seemed difficult for each of the professors to talk to each group individually”. We admit that the equipment developed problems during deployment that are mainly due to the compacted wiring and exposed electronics. A more reliable design has almost been completed and would be tested prior to the next implementation.

c. **More professor/teaching assistant (TA) involvement/ each group should be taken through the motions.** About 14% (3 out of 21 respondents) want more
professor/TA involvement in guiding the groups through the learning experience which implies less student self-directedness. A typical student comment on this is: “More teacher involvement, less him wandering around the class asking us our questions back to us”. This comment refers to the self-directedness built into the CHAPL pedagogy and the dissatisfaction some students have with it. The professor’s and TA’s typical response to student questions is to direct them to the answer via a modified Socratic dialogue [13-15, 27]. For instance, in answer to a question the professor or TA directs the students to a page in the relevant text, asks him/her to read it and ruminate on what it means. We find that often the student arrives at the correct answer. In cases where they still do not arrive at a satisfactory answer even after persistent directions, the instructor explains it to them. However we understand some students’ dissatisfaction with this new approach because they are unfamiliar with it and we aim to explain to them the rationale behind it prior to future implementations.

d. **More time.** Some students (about 10% or 2 out of 21 respondents) believe that more time for the CHAPL class would be expedient. One student has this to say: “Maybe it'd be cool if we had more time for the activities like if class was a bit longer. I also liked when there was a very short lecture at the end of class like 5 minutes wrapping up the ideas”. We agree that it does take time to go through all the activities in the CHAPL and make sense of it for a lot of students. We have strived to make most of the activities fit within the 50-minute period and encouraged students to do the rest as homework. We also have office hours and
encourage students to utilize them. We think that adding more time to an already full time table is akin to extending the number of hours in a day.

e. More credit: Many students have complained that they have to do more work in this 2-credit class than in other 3-credit classes they are enrolled in. One student has this to say: “It should not be a 2 credit class, when we had more HW than a 3 credit course. Either knock out some HW or add a credit and make it three days a week.” We think this position could be a reflection of the students’ achievement goal orientation [73]. Many students in this class appear to have performance approach and work avoidance orientations. In the former orientation, they are more focused on their grades than on the learning itself and in the latter they are trying to minimize what they have to do (balancing payoff and effort). Even though it sounds reasonable to allot more credit for self-directedness, we believe a more helpful approach would be to encourage students to adopt a mastery orientation (an orientation where they are really focused on the learning itself and not on immediate extrinsic payoff).

V. Summary and Conclusions

In this paper we have presented a study to probe differences between traditional lecture and a new pedagogy where elements of CHAPL and lecture are both used. Many interesting developments arose from analyses of the results which have significant implications for learning experience and assessment design.

A comparison of an examination question for a traditional lecture topic on one hand separately to two examination questions for CHAPL cum lecture topics on the other, showed no significant
difference. Even though the statistical power was low due to small sample sizes, students demonstrated, as measured by the particular assessments used in this study, about the same grasp of the material from the differently presented topics. This interpretation is necessarily qualified and limited because the questions used were different and the prior knowledge of the students on the topics was not gauged.

In order to gather more information on exactly how each element of the learning intervention impacts the different cognitive and affective dimensions important in the domain of FMHT, a survey designed based on Fink’s cognitive dimensions (foundational knowledge, application and integration) Fink’s affective dimensions and Principles of Good Practice in undergraduate education, was administered and the results analyzed. The survey results indicate that students perceived that the CHAPL component of the implementation was more useful for application of domain principles and the lecture component was more useful for inculcating foundational knowledge in the students. This suggests the design of a controlled study to further confirm or refute this perception. In some of their comments, students suggested that the CHAPL component would benefit from a short pre-lecture to build up their knowledge base prior to other types of learning (akin to “scaffolding” in cognitive apprenticeship [74]), a position supported by the extant literature. Furthermore, the results indicate varied student responses about which of the components had more positive impact on the integration dimension of cognition. This may well be attributable to varied learning styles and could also be sorted out in a controlled study.

An analysis of the results for Fink’s affective outcomes show clearly that the CHAPL helped more than lecture to develop the human dimension (group work skills) and independent learning skills. This is attributable to the inherent characteristics of the CHAPL pedagogy. Furthermore,
students reported that the lecture component of the implementation helped them to care more about FMHT in everyday life than did the CHAPL component. This could be attributed to the lecturer introducing common everyday examples of FMHT as opposed to the CHAPL which focused more on industrial examples.

In addition, analyses of the PGP components of the survey (viz student-instructor interaction, student-student interaction, active learning, time on task, high expectations and learning in diverse ways) indicate that the student perceive and appreciate the inclusion of PGPs in this implementation.

An analysis of recommendations made by the students showed they would like improvements in the following aspects of the learning intervention: pre-activity lecture on the modules prior to the related activity (more foundational knowledge), DLMs (prevent malfunctioning), professor/TA involvement (more guidance), time (to complete more activities in class), credit (increased from 2 to 3 because of the workload). These recommendations will be examined with a view to determining their merit and implementation feasibility.

Overall, we perceived mixed responses to the different components of this implementation and aim to take the issues raised and recommendations made into consideration when designing future learning interventions.

**VI. Future Research Directions**

Some questions arise from this study that we aim to answer in subsequent work. For instance, the surveys indicated that different facets of this implementation affected different Fink’s taxonomy dimensions of cognition, i.e. foundational knowledge, application and integration. We aim to do
a study with an experimental CHAPL group and a control group with just lecture as the independent variables and rubric scores for the different cognitive dimensions as the dependent variables. Our research question would be: for the same topic and the same assessment artifact, would we find that the group of students taught using only CHAPL does better on the application aspect of the artifact than the lecture group? We believe that assigning rubric scores to these different dimensions of cognition represents a more holistic and profound means of measuring cognition and tracking the intellectual growth of students than say GPA or lump test scores. While work to develop a rubric based on these dimensions has been initiated by our group it will be further developed and tested by a panel of professors in the field of FMHT to ascertain the validity and universality of the constructs and levels of performance in the rubric. This panel will, among other things, decide what constitutes foundational knowledge, application, and integration for each artifact. Panel members will also decide if there are any overlaps (for instance when a particular element of cognition in the domain may be regarded as both foundational knowledge and application) and resolve discrepancies in the form that each member believes a certain element of cognition ought to take (for instance one member may feel that an equation suffices to show understanding of a particular point while another may believe that a detailed explanation is necessary; a consensus that involves one or both views needs to be reached in such a case) before deployment of the rubric. Furthermore, to imbue the study with higher statistical power, the number of participants, N will be increased by pooling participants of a comparable level of intellectual development (in this case juniors) who take FMHT from different programs (e.g. mechanical engineering and chemical engineering) and/or universities.
Acknowledgements

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References


46. Golter, P., B.V. Brown, D. Thiessen, and B. Abdul. *Shifting gears: Moving Away from the Controlled Experimental Model While Improving Rigor in Engineering Education*
Research. in 2010 American Society for Engineering Education Annual Conference and Exposition. 2010. Louisville, Kentucky.


66. Reeves, T.C., J. Herrington, and R. Oliver *Authentic activities and online learning.* 2002. 9, 562.


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**Gary Robert Brown** has been in higher education for more than 30 years. He has an interdisciplinary PhD and has been working with colleagues in almost every discipline. His expertise is in educational assessment with a strong background in technology and innovations. Dr. Brown was lead developer of WSU’s well-recognized Critical Thinking rubric, now used at 100s of institutions worldwide. Gary has received best research awards seven times and has been active in several professional organizations including American Association of Colleges and Universities (AC&U) and the American Evaluation Association (AEA). His current focus has been on accountability and accreditation and working with several regional and professional associations to assure accreditation efforts are increasingly useful for faculty involved in assessment. He can be reached at: browng@pdx.edu

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CHAPTER FOUR

Pedagogical Influences on Learning Gains in a Fluid Mechanics and Heat Transfer Class

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Abstract

Background

The instructor-student expertise differential is assumed to provide a unique opportunity for instructors to impart knowledge to students. However, theoretical and empirical research suggests that learning is enhanced when instructors present information in such a way that it minimizes cognitive load. Multimedia learning including multimedia-enhanced lecture (MEL) and hands-on interactive group learning (HAL) are two good learning strategies to reduce this cognitive load.

Purpose/Hypothesis

This paper describes a study in which HAL and MEL are compared. Significant cognitive and affective advantages of HAL were expected because of the use of engineering hardware and active learning.

Design/Method

An experimental design was used where two groups, HAL and MEL, alternated between being the control and treatment for either of two topics. Concept tests, worksheets and surveys
completed were assessed for cognitive and affective outcomes based on a Fink’s Significant Learning Taxonomy (FSLT).

**Study Outcomes**

The majority of participants agree that HAL is more realistic and facilitates better cognition and professional preparedness. Surveys reveal high effect sizes ($d = 0.8-2.0$) in favor of HAL. However, assessment scores show no statistical intergroup differences. Importantly, no significant learning impairment is perceived from replacing MEL with HAL while most students report that the hands-on equipment gave them better real-world experience.

**Conclusions**

No deleterious effect was perceived from HAL and it is more beneficial than MEL in terms of solidifying schema (longer term retention) and providing other benefits of competency-based education such as group skills, engaging learning and realism.

**Keywords**: cognitive load, multimedia enhanced lecture, hands-on active learning, Fink’s Significant Learning Taxonomy.
Introduction

Ongoing research on enhancement of cognitive and affective learning outcomes in Science, Technology, Engineering and Mathematics (STEM) disciplines [1-6] is necessitated by educational stakeholders’ concerns about declining cognitive performance of learners especially in tertiary institutions [6, 7]. For the engineering domain, the Accreditation Board for Engineering and Technology (ABET) has outlined criteria for important learning outcomes including the ability to apply STEM knowledge and identify, formulate and solve engineering problems [8].

Engineering education researchers have published many instructional designs or pedagogies that report a cognitive edge over straight lecture [9-13]. These include pedagogies of engagement [12] such as Problem-Based Learning (PBL) [14-17], hands-on learning [18-27], interaction-enhanced lectures [13] and multimedia-aided deliveries [23, 28-41]. All of these pedagogies involve certain qualities and quantities of multimedia learning delivery and therefore different effects on cognitive load [42-46]. As has been pointed out in Cognitive Load Theory (CLT) [47] the goals of instructional designs are, or at least should be, the reduction of extraneous cognitive load and increasing of working memory capacity given that learner-specific intrinsic cognitive load is unalterable [46, 48-50].

Fink in his Significant Learning Taxonomy [51] identified three synergistic (non-hierarchical) cognitive dimensions important to learning, namely Foundational knowledge (F), Application (A) and Integration (I). A measurable enhancement in any of these dimensions might suggest a reduction in cognitive load. Also significant differences between treatment and control groups would suggest more cognitive load reduction by one pedagogy over the other since performance scores have been identified as an indirect but objective measure of cognitive load [42].
Several studies have indicated that each of these cognitive dimensions could be enhanced by different pedagogical interventions. One approach is to use a student interactive strategy. For example, Dochy and colleagues in 43 medical classrooms [14] found that students who experienced project-based learning or PBL showed better knowledge application outcomes than those who learned the same thing through lecture, with a weighted effect size of 0.46, while lecture was better but not practically significant for foundational knowledge, with a weighted effect size of 0.22. In this meta-analysis, PBL was taken to mean small group, student-centered, instructor-facilitated, authentic problem-driven learning, with plenty of self-direction. Another meta-analysis by the same authors found that PBL students performed better on the linking of concepts and principles, with a weighted effect size of 0.80, while lecture and PBL students performed similarly on understanding of concepts, with a weighted effect size of 0.07 [52]. Springer, Stanne and Donovan’s meta-analysis [53] showed a higher cognitive outcome in a PBL small group over a lecture group in STEM disciplines (effect sizes: 0.51 for cognition, 0.55 for attitude and 0.46 for persistence). Prince’s meta-analysis [54] showed that active learning outperformed lecture with effect sizes greater than 50% but cautions on the localization limitations of research in education (i.e. importance of study context, as it is possible that some other trend could be found in some other study). Hake’s [55] and Redish’s [56] studies stand out for using more than one measure to quantify cognition. Hake’s study involving more than 6000 students from 62 different introductory physics classes at different US Universities, Colleges and High schools found improved conceptual knowledge gains for interactive learning, where teams of two or more discuss and select from a list of multiple choice short answers to a conceptual prompt from the instructor, over straight lecture group using the Force Concept Inventory (FCI) [1] and application of concepts using the Hestenes-Wells quantitative Mechanics Baseline Test (MBL) [2]. The aver-
age normalized pre-post gain on the FCI for the interactive group of 0.48 ± 0.14 (N = 4,458) was significantly higher than that of the more passive group with a gain of only 0.23 ± 0.04 (2084). The MBL, a posttest only, results were well correlated with the FCI scores with the interactive group doing better (average score of 60% vs. 40%). Redish reported learning gains for computer-based active-engagement tutorials over traditional tutorials using FCI as a test of foundational knowledge and a free-response question as a test of application of principles. The FCI pre-post improvement as a percentage of maximum possible gain for the tutorial groups on all questions was 52-77% while for the lecture group improvements for the same questions was only 11-48%.

On top of interactive learning, an instructor may add a hands-on approach. Easley and co-workers [57] (in press), comparing highly visual miniaturized desktop open-channel-mediated collaborative learning to lecture found the former was better with an effect size of 0.98. In another study, Burgher and co-workers found that hands-on group learning tends to help more with application and lecture helps with learning of foundational knowledge [58]. Linsey and co-workers in a Materials class found cognitive gains for lecture with hands-on over straight lecture with an effect size of 1.6 [59]. This result was augmented by a student survey in support of the hands-on exercise. Abdulwahed and Nagy measured statistical significantly better performance in a treatment group (average score of 57%) which had a virtual laboratory preparation before hands-on exercise compared to a control group (average score of 45%) that had the same hands-on exercise without the virtual pre-lab [60] indicating the importance of pre-lab before hands-on experience.

Dual coding theory, which posits that the human mind processes verbal and visual information using two separate and independent channels, is very important as it suggests that multimedia instruction consisting of verbal and visual components would make more efficient use of human
cognitive architecture and lead to better learning [61]. For example, Downs et al. used lecture, iPod and computers to deliver learning on descriptive statistics in a 3X2 study [62]. They found that those who experienced dual mode presentations via iPod or computers had a test score average of 9.8 ± 0.3, which was significantly better than those who only had lecture with a test score average of 8.4 ± 0.4. Also, an audio/visual group (average score of 10.6±0.4) significantly out-performed the audio/text group (9.0 ± 0.4) and the audio group (8.4 ± 0.4).

Other studies have found no statistical interpedagogical differences. For example, Yadav and colleagues [63] found no difference in conceptual understanding in two mechanical engineering topics between case study and lecture students using a single concept score. However, a survey administered to the same students reveals that 79% believed that the cases added more realism to the class, 69% believe it is more thought provoking and 64% believe it was more relevant to learning the course concepts. Chenkin et al. [40] also found no statistically significant cognitive or affective difference between a web-based group who used online tutorial and a straight lecture to learn a medical procedure. Damewood and colleagues [39] also found no difference between a group that used a multimedia simulator and another which used a physical human model to learn skills on Focused Assessment with Sonography for Trauma (FAST). They did not, however, survey the two groups on their perceptions. Seabra et al. [41] also found no cognitive difference between students who experienced multimedia presentation via computer and students who experienced a straight lecture on the same urology topic. However, 74% of the multimedia group reported in survey responses that an instructor is still important suggesting that multimedia presentation should be instructor-mediated. These studies demonstrate the importance of using multiple assessment instruments in determining the overall impact of an implementation as further insights are gained, albeit at times from a self-report survey or interview mechanism.
In summary, there is strong evidence that enhanced cognitive outcomes are achieved through use of either interactive, hands-on interactive, or multimedia approaches, suggesting different effects on cognitive load engendered by the different designs. Furthermore, where no statistical advantage is shown the use of other measurement instruments may shed further light on relative advantages or reveal student consensus on what may be used to improve an approach. Some studies shed more light on learning gains through assessment of both cognitive and affective outcomes through multiple measurement instruments. Unfortunately however, many studies only report on one cognitive outcome using just one assessment instrument applied to a single artifact such as one test or project score. When contrasting two or more implementations, both of which have been shown to improve learning, these latter approaches are particularly important.

In the present paper, we report the outcomes of a controlled study where two different instructional designs, MEL (control) and HAL (experiment) were used to teach two crucial Fluid Mechanics and Heat Transfer (FMHT) topics, the shell-and-tube heat exchanger (STHX) and a new water flow through spring coil and air cross flow system [64], used to demonstrate evaporative cooling concepts, that we call the evaporative cooling heat exchanger (EVHX). Although it is reported in extant literature that these two pedagogies engender better learning outcomes than straight lecture, it is not yet known how they compare to each other, and hence the focus of this study. The overarching research question is:

What are the effects of learning with a hands-on active strategy compared to a multimedia-aided lecture?
The processes in the instructional designs, the assessment artifacts or tests, and assessment approaches are described in light of corresponding underlying theories with a view to discerning factors responsible for any differences in cognitive and affective outcomes.

**Human Cognition and Cognitive Load Theory**

The human cognitive architecture (HCA) consists of a vast long-term memory (LTM) which is analogous to the hard drive on a computer and the limited short-term or working memory (“central processing unit, CPU”), which is the center of task execution. The LTM contains disjointed facts and poor schemas for novices, and sophisticated schemas (highly organized cognitive structures like concepts and skills) analogous to “neat” folders for experts. Additionally, schemas no matter how complex can be stored in working memory as a single unit and will become automated with continuous usage. When faced with a task, information can pass into working memory through the LTM and/or the senses analogous to a keyboard (senses) communicating information to a hard drive [46, 47] with the flow process more efficient for experts. The limitations of this central executive for novices, necessitates effective instructional design to bridge the gap. In other words, effective instructional design that enhances schema construction should serve as the central executive, or basis on which task execution protocols are built, for the novice.

The Baddeley model ([61]) divides working memory into two independent subsystems: the visuospatial which processes visual (written text and pictures), spatial and haptic (tactile/kinesthetic) information; and the phonological which processes auditory (narration, environmental sounds and music), signs and lip reading information. He also proposed episodic buffers such as smell and taste that mediate between the two subsystems. These subsystems are believed to be independent because deficiency in one is not compensated for by the other [42]. Complementary to this theory is the generative theory of multimedia learning; one of its main postulates is dual-
coding which posits that verbal and visual information are \textit{processed} in separate but interconnected systems. The other is the dual-channel postulate which posits that visual and verbal information are \textit{perceived} in different subsystems. A useful principle that stems from these theories posits that more learning will occur when material is presented in formats that use both auditory and visual subsystems (i.e. multimedia) than by a format that uses either in isolation.

The cognitive load theory (CLT), which seeks to explain resistances to instruction and how to reduce them, was formulated based on a better understanding of HCA and postulates three important cognitive loads \cite{42, 50}, the \textit{intrinsic} cognitive load which is a characteristic of the topic to be learned, e.g., the number of cognitive elements and their interactivity, i.e. the complexity of the material, and the position of the learner on the trajectory of \textquote{knowing}, novice to expert, \textit{germane} cognitive load or that which is useful for learning (schema construction), and \textit{extraneous} cognitive load which is imposed by poor instructional design, e.g., inefficient processing of material irrelevant to learning. The sum of these loads should be less than available mental resources in order for learning to occur. For low intrinsic load material (simple topic, few cognitive elements, low element interactivity), the learner may have adequate mental resources to learn from a variety of sources even from such that impose high extraneous load. On the other hand, high intrinsic load material (difficult topic, many elements, and high element interactivity) requires more stringent instructional design that minimizes extraneous load or else learning will fail to occur.

\textbf{Group learning, Cognitive Load Distribution and Motivation}

A major advantage of collaboration in learning is the pooling of working memory capacity to solve a problem more effectively and/or more efficiently. This effect is more prominent for highly complex tasks (high elemental density and interaction, high cognitive load) and well-
coordinated group dynamics (good communication and planning). The distributive advantage of collaboration on complex tasks is also supported by brain research where inter-hemispheric processing advantage over mono-hemispheric processing has been shown [65, 66]. A complementary explanation for the advantage of collaboration over isolation in tackling complex tasks is increased self-confidence [67]. Group members are likely to feel more confident because of expected cognitive distribution. However, the contribution of the cognitive and affective factors is related to task complexity and collaborator skill levels.

However, the efficiency and effectiveness of collaboration begins to recede as task complexity decreases and may vanish or become disadvantageous as complexity vanishes. Furthermore, transaction (communication and planning) costs can cause an extraneous load or germane load depending on transaction management, and these costs become more important as the task complexity decreases. Kirschner et al.’s [68] and Janssen et al.’s [69] review articles on collaborative learning identified other cautions for historical collaborative learning research such as concern about research orientation (effect- or process-oriented), measures of performance (it’s best to compare each group member’s performance to individuals in the control group), and that the outcome measurement should be post-instruction rather than during instruction.

**Multimedia Learning and Cognition**

Multimedia learning refers to learning with multiple representations of the learning materials of interest including words (narrative and written), pictures (movies, images, sketches, simulations, schematics, charts) and physical models (prototypes and equipment). Because the two working memory subsystems which process visual and verbal information are independent and complementary [61], presenting information in both modes avoids overloading one subsystem and thus makes more efficient use of the working memory.
Methods

The study methodology employed in this research is firmly grounded in CLT and results are interpreted from this standpoint.

Study design

Thirty-eight (38) WSU chemical engineering juniors, 10 women and 28 men, were split evenly into two groups having balanced GPAs each alternating between the control or lecture group for STHX, and EVHX topics. The treatment group was split autonomously (p 75-76 of ref [70]) into 5 subgroups of 3 and 1 subgroup of 4 for the social construction of cognition built into the HAL, a subset of the pedagogy package dubbed CHAPL (Cooperative Hands-on Active Problem/Project-based Learning) [21, 71-73].

Procedures

The two DLM cartridges shown in Figure 1, an STHX and an EVHX,

![Figure 1](image-url)

**Figure 1.** (a) STHX cartridge (b) EVHX cartridge.
developed as an NSF project broader impact for bringing research into the classroom [64], were selected for probing associated learning outcomes. These topics are particularly rich in concepts, and foster use of design and analysis skills of importance in Chemical Engineering practice.

Figure 2. (a) Instructor interacting with a HAL group on the Evaporative heat exchanger (EVHX); (b) Instructor lecturing the MEL group on same topic.

The outcome of interest is growth in the three cognitive dimensions of FSLT [51], Foundational knowledge, Application and Integration (F, A, and I). Coded ~5 min pre- and post-quizzes, worksheets and exam questions were rated using a new FSLT rubric we developed [74] to probe for significant differences in cognitive dimensions. Also, an administered survey instrument in Likert format [75], included questions on the degree to which specific topics presented through HAL or MEL impacted or would have impacted growth in the FSLT dimensions. It also included questions on the degree to which the implementations used the 7 Principles of Good Practice in Undergraduate Education [76, 77]. Nonparametric Wilcoxon analysis [78], and written comments were used to assess perceptions about the relative value of the approaches.
Table 1. Major STHX and EVHX concepts.

<table>
<thead>
<tr>
<th>STHX</th>
<th>EVHX</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Thermal resistance, overall heat transfer coefficient</td>
<td>Thermal and mass transfer resistances, mass / heat transfer coefficients</td>
</tr>
<tr>
<td>2. Equipment architecture and its influence on individual heat transfer coefficients</td>
<td>Equipment architecture and its influence on the heat transfer coefficient</td>
</tr>
<tr>
<td>3. Hydrodynamic and thermal boundary layers</td>
<td>Hydrodynamic, thermal and mass transfer boundary layers, wet &amp; dry bulb temperatures, relative humidity, psychrometrics</td>
</tr>
<tr>
<td>4. STHX design / optimization</td>
<td>EVHX design / ways of improving heat transfer</td>
</tr>
</tbody>
</table>

Table 1 summarizes the main concepts for each topic while Table 2 outlines the implementation. Figure 2 (a) shows the instructor using the EVHX with the HAL and 2(b) shows same instructor lecturing the MEL group on the same topic. Notice that HAL is more learner-centered than MEL.
Table 2. Pedagogical implementation.

<table>
<thead>
<tr>
<th>Topic</th>
<th>Lecture</th>
<th>Hands-on</th>
</tr>
</thead>
<tbody>
<tr>
<td>STHX</td>
<td>5-7 min STHX prequiz (prior date)</td>
<td>5-7 min EVHX prequiz (prior date)</td>
</tr>
<tr>
<td></td>
<td>43 min STHX lecture</td>
<td>10-13 min pre-lecture.</td>
</tr>
<tr>
<td></td>
<td>Realistic STHX data given</td>
<td>3D animation of 1-2 STHX (architecture &amp; flow pattern)</td>
</tr>
<tr>
<td></td>
<td>3D animation of 1-2 STHX (architecture &amp; flow pattern)</td>
<td>Picture of industrial scale STHX</td>
</tr>
<tr>
<td></td>
<td>2D diagram of a 1-2 STHX &amp; 2D of a U-tube exchanger</td>
<td>Picture of STHX cartridge</td>
</tr>
<tr>
<td></td>
<td>Picture of industrial scale STHX</td>
<td>25-30 min activity</td>
</tr>
<tr>
<td></td>
<td>Picture of STHX cartridge</td>
<td>Groups manipulated controls &amp;took measurements while discussing worksheet</td>
</tr>
<tr>
<td></td>
<td>STHX analysis</td>
<td>concept questions with instructor facilitation</td>
</tr>
<tr>
<td></td>
<td>5 min posttest on STHX</td>
<td>5 min posttest on STHX</td>
</tr>
<tr>
<td>EVHX</td>
<td>~50 min: EVHX worksheets handed out with realistic data</td>
<td>~15 min: Geometry &amp; flow patterns of cooling towers</td>
</tr>
<tr>
<td></td>
<td>Basic geometry &amp; flow patterns of cooling towers</td>
<td>Photos of industrial scale cooling tower flow pattern</td>
</tr>
<tr>
<td></td>
<td>Photos of industrial scale cooling tower flow pattern</td>
<td>Briefing on experiments</td>
</tr>
<tr>
<td></td>
<td>Photos &amp; 3D CAD drawing of EVHX cartridge</td>
<td>20-25 min 3-member groups performed experiment &amp; discussed worksheet</td>
</tr>
<tr>
<td></td>
<td>Theory &amp; analysis of cooling towers: enthalpy balance/ geometric parameters</td>
<td>with instructor facilitation</td>
</tr>
<tr>
<td></td>
<td>Details on how to use psychrometric charts</td>
<td>~10 min analysis lecture: enthalpy balance/ determining geometric parameters</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Very brief instruction on using psychrometric chart (due to time constraint)</td>
</tr>
<tr>
<td></td>
<td>5 min posttest on EVHX</td>
<td>5 min posttest on EVHX</td>
</tr>
</tbody>
</table>

**Design of assignments**

Assignments were based on the principles of authentic assessment [15, 79-82], designed to elicit responses revealing students’ understanding or lack of, and reflect the cognitive dimensions, F, A and I, of FSLT [51] (see Table 3). Quizzes consisted of conceptual questions expected to elicit answers that infer competency in these dimensions.
Table 3. A brief description of Fink’s cognitive dimensions.

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Description</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>Foundational knowledge</td>
<td>Knowledge and understanding of principles and relationships between them; recall of models; significance of parameters.</td>
<td>Recalling &amp; understanding terms in the energy balance, correctly defining and understanding physical significance of parameters.</td>
</tr>
<tr>
<td>Application A</td>
<td>Using principles to explain observed physical phenomena; solve particular problems; critical, creative &amp; practical thinking.</td>
<td>Reducing the general energy balance to suit a particular problem; using signs &amp; other professional conventions; critical analysis.</td>
</tr>
<tr>
<td>Integration I</td>
<td>Connecting principles within a domain (intra-domain) or connecting principles across different domains (inter-domain).</td>
<td>Connecting flow, heat &amp; mass transfer and economics; Reynolds number determines flow regime used to select the Nusselt number correlation.</td>
</tr>
</tbody>
</table>

**Design, development, deployment of rubric and associated assessments**

Our scoring rubric, detailed in ASEE conference proceedings [74], was based on the cognitive dimensions of FSLT and principles of rubric design [83, 84]. The development and deployment of the rubric was done using Belfer and colleagues moderator-facilitated convergent participation model (CPM) [85] and the Educational Testing Service (ETS) criterion of at least 70% inter-rater agreement (IRA). Design commenced by outlining the cognitive dimensions, descriptions of the dimensions and levels of performance, numerical scores for each level and anchoring scores to letter grades for ease of scoring by faculty. During the development and testing of the rubric, the descriptions of what constitute foundational knowledge (F), application (A) and integration (I) of knowledge specific to the topics of interest were negotiated, assignments exemplifying the various levels of cognitive performance identified and discussed, and modalities for pairwise inter-rater agreement outlined. A minimum competency level (MCL) of 3.0 or B- was selected as the point where significant learning is deemed to commence. Inter-rater agreement was reached by two different raters comparing scores for a particular answer and discussing reasons why scores differ by more than an agreed margin of 1 point out of 5, using the provisions of the rubric as a
guide [85]. Table 4 shows an excerpt from the rubric detailing its architecture for the Foundational Knowledge dimension. Gains from rubric assessments were tested for statistical significance and effect sizes. Gains were computed thus:

\[ \text{Gain} = \frac{\text{Post Score} - \text{Pre Score}}{\text{Maximum Score}} \]
Table 4. Excerpt from WSU Fink’s rubric [74].

<table>
<thead>
<tr>
<th>Rubric dimension</th>
<th>Scores</th>
<th>Letter grades</th>
<th>0</th>
<th>0.5</th>
<th>1</th>
<th>1.5</th>
<th>2</th>
<th>2.5</th>
<th>3</th>
<th>3.5</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Foundational knowledge</strong></td>
<td><strong>Recall basics i.e.:</strong></td>
<td>Score Levels (Significant Learning Anchor = 3 or B-)</td>
<td>0</td>
<td>0.5</td>
<td>1</td>
<td>1.5</td>
<td>2</td>
<td>2.5</td>
<td>3</td>
<td>3.5</td>
</tr>
<tr>
<td></td>
<td>No Evidence of correct definitions / equations.</td>
<td>Evidence of sketchy, disjointed explanations of FMHT principles.</td>
<td>Evidence that equations / explanations of FMHT principles appear correct but lack enough substance to be considered complete.</td>
<td>Evidence that equations / definitions complete and correct.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Explanations incoherent &amp; obviously have no bearing on knowledge of FMHT principles.</td>
<td>Equations incomplete/inconsistent with system, dimensional inconsistency.</td>
<td>Equations essentially complete but lack some significant terms.</td>
<td>FMHT explanations / principles complete &amp; perfect; thorough understanding of foundational principles as evident from explanations / usage of models / drawings.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Linkage between parameters in explanation is confusing / inarticulate explanation.</td>
<td>Patchworks of correct ideas, sometimes contradictory (e.g., opposite ideas on the same principle in different parts of problem; correct in one sentence and wrong in the next).</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Show understanding via explanations, rationale for choices.</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Results and Discussion

Inter-rater agreement
IRAs on 25% of the assignments of 67-100% were achieved before norming and narrowed to 83-100% after norming all of which are greater than the ETS criterion of 70%. High initial values indicate raters were well trained in the deployment of the rubric since they were familiar with it from a previous study [74] and suggest an objective, reproducible and reliable scoring process was conducted. One of the raters proceeded to rate the remaining assignments.

Outcomes – cognitive gains
Cognitive load reductions by instructional designs are typically assessed by relative scores on assessments of technical expertise [42-46]. Applying that strategy to the present study, MEL and HAL appear to have reduced cognitive load by a similar amount. This is visually evident in Figures 3 and 4, scatter plots of pre and post scores on STHX and EVHX concept tests along Fink’s F, A and I dimensions. First we note the majority have low average pretest scores, below the MCL of 3, indicating both groups had inadequate schemas in their long-term memory (LTM) from previous instruction. Plots show fairly similar trends with individuals generally improving and 58 – 91% of the post scores above pre scores for most indices. Exceptions occur for the EVHX for the A dimension lecture (42%) and I dimension hands-on (46%). Regarding our significant learning benchmark or MCL of B- (3.0) again in the majority of the cases, 55 to 92% of the students, either attained or exceeded the goal. Exceptions appear in all cases for the EVHX A and I indices with a mere 23 – 50% reaching the MCL in either teaching mode. This could be because the EVHX is a new topic and material cannot be found in texts or web resources.
Visual analyses are corroborated statistically. First, there were insignificant differences on the STHX and EVHX pretests suggesting both groups had similar prior knowledge in these domains and are cognitively matched. Both groups improved on posttests and final exams over pretests. However, Table 5 reveals insignificant differences in learning gains in pre/post, pre/finals and post/finals between the two groups on posttests which suggest, on average, similar cognitive growth. The only exception is a decrease in I for both groups on the post test. While there are minor losses in F and I in particular for the STHX between the posttest and final, there are gains across the board for the EVHX attributable to the students having more time to digest this new material. From the collective evidence it is not unreasonable to suggest further that the two instructional designs may have reduced intrinsic cognitive load by the same degree.

Given that learners in the two groups started out at the same point on the cognitive trajectory (comparable pretests), we can safely assume that the material on the posttest will present the same intrinsic cognitive challenge and therefore the same performance only if the two different instructional interventions gave rise to the same level of working memory management [50, 86] or the same level of cognitive load reduction. This means that both groups encountered all the elements of cognition and their interrelatedness necessary for answering the questions in such a way that cognition is indistinguishable by the rubric. Also, despite the expected group collaborative ‘spreading’ of working memory load in the experimental group, no significant difference was discerned. The collective working-memory effect [87] suggests that collaborative learning is more efficient for high complexity tasks because of the distributive potential over many working memories. The authors however hasten to caution that a member who has highly defective schemas can inadvertently lower the sum of the working memory capacities akin to the expertise reversal effect [49]. Another, though affective, explanation for this collaboration effect is that
learners who expected to solve a complex problem in a group, reported less mental effort expectations while learners who expected to do it alone reported the opposite [67]. This suggests that the former category already had a higher expectancy of task-related efficacy which provides higher motivation for tackling the task. Based on this argument and the ‘flat’ intergroup performance profile, the tasks inherent in the questions used in this study may be classified as being of inadequate complexity to make efficient use of the added collaboration or ‘distributed working memory’ in the experimental group.

Figure 3. STHX post vs. pre Fink’s scores. Significant numbers are above the parity line (diagonal) and at or above the horizontal minimal competency of 3 (B-) for F, A and I dimensions both the lecture and hands-on.
Figure 4. EVHX post vs. pre Fink’s scores. Significant numbers are above the parity line (diagonal) for F, A and I. Fewer, reach minimal competency of 3 (B-) than for the STHX.
Table 5. Gains showing statistically insignificant differences (0.14 ≤ p ≤ 0.97).

<table>
<thead>
<tr>
<th></th>
<th>MEL: M (SD)</th>
<th>HAL: M (SD)</th>
<th>Effect size(\dagger) (p &gt; 0.05)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N F A I</td>
<td>N F A I</td>
<td>F A I</td>
</tr>
<tr>
<td>STHX</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre/Post</td>
<td>15 32(31) 30(33) 32(39)</td>
<td>18 26(36) 24(32) 29(34)</td>
<td>.18 .19 .08</td>
</tr>
<tr>
<td>Pre/Finals</td>
<td>16 24(23) 28(26) 23(33)</td>
<td>17 25(28) 29(27) 26(29)</td>
<td>.04 .04 .10</td>
</tr>
<tr>
<td>Post/Finals</td>
<td>17 -13(23) 1.5(31) -6(35)</td>
<td>19 -8(23) 2(31) -3(36)</td>
<td>.22 .02 .08</td>
</tr>
<tr>
<td>EVHX</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pre/Post</td>
<td>15 26(23) 11(50) -3(60)</td>
<td>15 3(57) 13(53) -23(84)</td>
<td>.63 .04 .28</td>
</tr>
<tr>
<td>Pre/Finals</td>
<td>15 22(23) 24(25) 24(35)</td>
<td>18 10(26) 14(20) 7(28)</td>
<td>.49 .45 .54</td>
</tr>
<tr>
<td>Post/Finals</td>
<td>14 11(27) 15(27) 16(32)</td>
<td>15 3(26) 3(27) 11(29)</td>
<td>.30 .44 .16</td>
</tr>
</tbody>
</table>

\(\dagger\)Effect sizes are absolute values; the reader should note group with higher gain.

A further investigation of relevant questions in final examination written two months later also revealed no overarching significant intergroup differences suggesting the groups on average had acquired the same near-transfer and medium-term cognitive retention capacities. Instructional implementation notes reveal both groups were given PowerPoint presentations (simultaneous imagery and narration) of the architecture, principles, and processes involved in the STHX and EVHX. The experimental group had the PowerPoint presentation for a shorter time using the rest of the time for student-student, student-DLM and student-instructor interactions. It is therefore possible that both groups apprehended the cognitive elements required nearly to the same degree during the PowerPoint presentation, and thus the 3D imagery and animation, flow of water, fan blowing, and change of physical variables on screen, and more animated discussion with peers and instructor, were redundant [43, 49, 86], or that the HAL group had partial grasp of content.
from the PowerPoint and only an equal grasp as the control group after subsequent hands-on collaboration. It is also noteworthy that 78% of the cognitive outcomes from the final examination were above the MCL of 3 suggesting that both instructional designs created significant learning [51] even though it is difficult to isolate the contribution of each.

Table 6 shows several worksheet questions and one final exam question in which the multimedia rich lecture group significantly (p < .05) or nearly significantly (p < .1) out-performed the hands-on group and in which large effect sizes were found. In these few instances where results support stronger cognitive gains through multimedia lecture the findings are not surprising as the learned attributes relate to factual knowledge, a list of steps provided to students on optimizing a heat exchanger, a formula given in class (and not found in any textbook) for EVHX surface area, a demonstration of how to use a graphical solution approach and a thorough lecture (more time) about design changes for enhancing heat exchange.

Table 6. Analyses where MEL appeared advantageous.

<table>
<thead>
<tr>
<th>Question nature</th>
<th>Dimension</th>
<th>Hands-on M(SD)</th>
<th>Lecture M(SD)</th>
<th>p; Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>STHX WS: Advantages of a double-tube pass STHX?</td>
<td>A</td>
<td>1.4(1.1)</td>
<td>2.1(1.2)</td>
<td>.07; .61</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>1.1(1.1)</td>
<td>2.2(1.4)</td>
<td>.01; .89</td>
</tr>
<tr>
<td>STHX WS: Economic tradeoffs in optimization?</td>
<td>F</td>
<td>2.5(1.1)</td>
<td>3.2(0.9)</td>
<td>.05; .72</td>
</tr>
<tr>
<td></td>
<td>I</td>
<td>1.9(1.2)</td>
<td>2.6(1.1)</td>
<td>.09; .61</td>
</tr>
<tr>
<td>EVHX WS: Water surface / unit volume of fill material.</td>
<td>F</td>
<td>3.0(1.3)</td>
<td>3.7(0.8)</td>
<td>.07; .69</td>
</tr>
<tr>
<td>EVHX WS: Compare correlated to experimental heat duties.</td>
<td>A</td>
<td>3.0(0.9)</td>
<td>3.6(0.8)</td>
<td>.05; .71</td>
</tr>
<tr>
<td>STHX Final: Enhancement of shell-side heat transfer coefficient?</td>
<td>A</td>
<td>2.3(1.4)</td>
<td>3.3(1.1)</td>
<td>.04; .81</td>
</tr>
</tbody>
</table>
Self-report gains

Experiential hands-on and collaborative learning have been reported as creating longer-term retention and farther transfer than narration-based pedagogies [67, 88, 89]. To elicit student perceptions on how the pedagogies influenced their cognition in the F, A and I domains, survey prompts were designed. Figure 5 shows students perceive better cognition from hands-on group learning than lecture for both topics. Table 7 presents a nonparametric statistical Wilcoxon signed-rank paired difference test analysis allotting numerical values for the Likert-type responses. To reduce bias converse prompts were given, e.g., ‘Hands-on group learning (or Lecture) helped /would have helped more than lecture (or hands-on …) to understand the basic principles of Shell & Tube heat exchangers’. The very large effect sizes of 0.8 to 2.0, and p-statistics < 0.05, except in one instance of 0.09, show students perceived better cognition from the hands-on group learning than from multimedia-enhanced lecture for all cognitive dimensions probed. An analysis of the free response data yields insights into students’ perceptions that fall into three basic categories each addressed in the following sections.

Visual reinforcement of cognition

The responses to: ‘Contrast your learning from lectures with that from the other activities (hands-on, group work and demonstrations)’, showed a mix of perceptions from those solely in favor of hands-on (50%) through mixed (hands-on and lecture equally useful and complementary, 31%) to those solely favoring lecture (19%).

Respondents in favor of HAL had a variety of reasons the most prominent of which pertained to the visual and tactile reinforcement of cognition such as “I thought overall the hands-on was better because you were able to actually see and make connections on how the module worked.” This statement could be interpreted as the student believes a visual learning experience was in-
valuable to metacognition. Another said: “In lectures you learn the concepts and the mathematical reasoning behind the project but you never gain a sense of its applicability. In the activities everything is much more free form and as an individual you have to reason out why things happen the way they do and so you gain a more solid understanding of the concepts.” This student seems to believe process visualization leads to better cognitive processing and retention of schemas. Furthermore, 64% of the students responded that HAL helped with application. In a related prompt, 53% of respondents said lecture helped most with foundational knowledge. Yet another student said: “It was very evident that the activities helped ‘stick’ the information in my head. Being a ‘tinkerer’ it was a very natural learning method”. This student is alluding to his belief that HAL is in sync with his learning style (active learning) [90]. Other reasons alluded to the group dynamics, analytical skills, and active learning. It is interesting to note that most of the factors alluded to have been identified as part of competency-based education [43]) which the university engineering programs accreditation body ABET has continued to emphasize [6].
Figure 5: Surveys on the three cognitive dimensions.

Respondents favoring a mixed approach suggested lecture was a necessary complement to hands-on. One had this to say: “I think demonstrations and hands-on are just as important as lecture. They both have their place. Hands-on is good because you get a better idea of what the physical significance of the calculation is. But lecture is important because theory is explained, trains of thought are explained and calculation is outlined.” Another wrote: “I learned a lot from the lectures. Though seeing what actually is going on when using the modules helped a lot.” Still another: “Lectures taught me the equations and principles, activities helped me understand the
knowledge more deeply and to be able to use it again.” These students seem to be alluding to lecture being better for presentation of facts and procedures while hands-on grounds these cognitive elements in real life. This position is buttressed by Gijbel et al’s meta-analysis of literature on Problem-based learning (PBL) and lecture which found that lecture students had slightly better basic knowledge than PBL students [52].

Table 7: Wilcoxon test statistical analysis of class survey (Nw’s [statistics in brackets] are calculated after excluding data for students who picked the same option for hands-on and lecture.

<table>
<thead>
<tr>
<th>Dimension &amp; topic</th>
<th>HAL better N=36 M(SD)</th>
<th>MEL better N=36 M(SD)</th>
<th>Wilcoxon test</th>
<th>Nw</th>
<th>Effect size (Cohen’s d)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FSTHX</td>
<td>3.9(0.9) [3.9(0.9)]</td>
<td>2.9(1) [2.7(0.9)]</td>
<td>&lt;.001</td>
<td>31</td>
<td>1.3</td>
</tr>
<tr>
<td>FEVHX</td>
<td>3.9(0.8) [4.0(0.7)]</td>
<td>2.9(1) [2.5(0.8)]</td>
<td>&lt;.001</td>
<td>25</td>
<td>2.0</td>
</tr>
<tr>
<td>ASTHX</td>
<td>3.9(1) [3.8(1)]</td>
<td>3.1(1) [2.9(1)]</td>
<td>0.03</td>
<td>28</td>
<td>0.9</td>
</tr>
<tr>
<td>AEVHX</td>
<td>3.8(1) [3.7(1)]</td>
<td>3.3(1) [2.9(1)]</td>
<td>0.09</td>
<td>24</td>
<td>0.8</td>
</tr>
<tr>
<td>IISTHX</td>
<td>3.7(0.8) [3.7(1)]</td>
<td>2.9(1) [2.8(1)]</td>
<td>0.04</td>
<td>29</td>
<td>0.9</td>
</tr>
<tr>
<td>IEVHX</td>
<td>3.7(1) [3.8(0.9)]</td>
<td>2.9(1) [2.6(1)]</td>
<td>0.01</td>
<td>28</td>
<td>1.3</td>
</tr>
</tbody>
</table>

About 19% of the responses showed a marked lecture preference while still acknowledging how hands-on activities enhance their learning. One reads: “I preferred the lecture over the hands-on. I work better with multiple examples and in-depth explanations. Having a demonstration solidified the information that was taught via lecture.” Another wrote: “I feel that the lectures helped me to understand the fundamental principles governing heat transfer more thoroughly; whereas the hands-on activities did not seem to be as well rounded and I had trouble converting the understanding I gained from the hands-on stuff to other systems. I would much prefer the lecture
over the hands-on. Bringing in modules did help though and should be included with the lecture.” These statements allude to this students’ learning style preference (intuitive and verbal) [90]. However, it has been reported that most learners tend to be more visual than verbal [90], a finding attested to by this survey – about half were attracted to visual and other elements of the hands-on learning while the other half are distributed between the other learning styles. Also, all these statements did suggest that lecture was more appropriate for understanding the fundamentals or Fink’s Foundational knowledge dimension.

Interestingly, the words ‘stick’, ‘solid’, ‘solidified’ and other synonyms used by over half of the survey participants in reference to HAL and demonstrations suggest long-term retention which has been identified by cognitive load theorists as the key objective of instruction [46]. While it is acknowledged that both pedagogies take advantage of the dual coding and dual channel theories [42], by using multimedia presentations, it appears students are attracted to the haptic (tactile/kinesthetic) component of Baddeley’s visuospatial subsystem [61]. It is not unreasonable therefore to state that students perceive better cognitive retention when principles are put into practice as happens during the deployment of the DLMs.

**Metacognitive processing**

A further analysis shows on average that about 80% of respondents were affirmative (~20% “strongly agree” and ~60% “agree”) that hands-on group learning encouraged them more than lecture to answer their own questions for both the STHX and EVHX activities while ~10% were neutral (“unsure”) and ~10% “disagree”. These responses suggest the hands-on activities encouraged students to develop metacognitive skills or active processing which in the long run helps them to be better learners. Also, 89% responded affirmatively (56% “much more” and 33% “somewhat more”) when asked if STHX worksheet was more beneficial to their learning than
textbook problems on the same topic, ~2.5% responded that it didn’t make any difference (“the same”) and 8.5% said it was less beneficial (6% “somewhat less” and 2.5% “much less”). EVHX responses again are quite similar. Following are typical responses:

“It was more interactive so it made it easier than textbook problems.”

“Worksheet was well organized. I can just follow the problem in the worksheet and understand the concepts easier.”

“ Took you through the steps to solve the problem in an understandable way.”

“The worksheet broke it down easier and in a clearer way. It helped walk you through the necessary steps whereas the book usually throws the whole problem at you all at once.”

“Compared to McCabe (the required text), the worksheet broke things down more and was more theoretical which helped in the learning process. McCabe’s problems usually feel too hard to learn with.”

“The worksheet was a more practical approach and made more sense intuitively than the book problems.”

Responses suggest that worksheets, designed and developed as a complement to hands-on pedagogy, gave students much needed guidance in constructing their own cognition (scaffolding and cognitive apprenticeship [91]). The worksheets foster a completion effect that emanates from CLT [46, 92] by essentially outlining and starting the solution to the problem for the learner to complete. Completion of problems is also believed to reduce extraneous load, and generate germane cognitive load which is important for schema construction [43].

Collaborative, real-world advantage

Aside from F, A and I, HAL is believed to impact other important areas of competency-based education, notably group dynamics and ill-defined problem solving. This is achieved by creating
a collaborative environment and assigning semi open-ended group projects at the end of the class. In response to a prompt about professional preparedness, ~83% agree they felt more prepared (53% “much more” and 30% “somewhat more”) for work in the field because of their experiences:

“Group work is good for preparation for professional practice, because almost all companies have employees work in groups. This makes the work go faster and allows for different points of view.”

“Working as a group helps develop team work and leadership skills. Hands-on will prepare us for possible career circumstances where we actually have to troubleshoot a real system based on data and not just plugging numbers into given equations. The project was also very insightful by giving introductory understanding of a simplified design.”

“Since I learned the material better with the hands-on work I feel more comfortable telling a future employer that I know how to design heat exchangers.”

“From my experience, the lecture environment is going to be the least common activity in our future careers but hands-on work, group work, projects and demonstrations will be our primary duties during our professional practice.”

“They emphasized the applicability of the concepts learned in lecture and showed how things work on the macro scale. A person can do all the simulations he wants in the virtual world but it won’t help get a feel of how things work in real life and that’s what the hands-on group work really gets at.”

In over 70% of the comments students say they appreciate analysis of real systems used in professional practice and the role of HAL in building their skills. They believe such learning solidi-
fies schemas by generating germane load [43] and collaboration will certainly be a part of their professional duties [68, 89].

**Conclusions and Recommendations**

Two pedagogies, a multimedia-aided lecture (control) and hands-on group learning (treatment) are used to presenting two topics – Shell & Tube and Evaporative Heat Exchangers with one group as the control in one experiment and treatment in the other. No significant difference in rubric-generated cognitive outcomes is perceived, suggesting both pedagogies are adequate for decreasing the intrinsic cognitive load such that the collaboration in the treatment group appeared redundant. It is possible that the hands-on active tasks in this study were of inadequate complexity relative to participants’ positions on the cognitive ladder to make efficient use of group working memory distribution in the treatment group. Perhaps a different population or examination of a more complex task for a similar population may produce a significant intergroup difference. Implementation of hands-on group learning may make a cognitive difference with freshmen for example and even enhance retention because of its “live” nature.

The relatively low scores on the EVHX concept questions, with >50% below the 3.0 benchmark, and seemingly persistent misconceptions, such as misunderstanding of the significance of the wet bulb temperature, noted in learners’ responses allow room for further investigation into plausible reasons and ways to overcome them. It could be some of these concepts need a more cogent visual reinforcement or that the mode of presentation needs to be modified.

Interestingly, an analysis of the survey responses reveals that students’ significantly prefer HAL. Written responses suggest this is related to their learning preference (>50% visual), beliefs that physical experiences lead to more robust and/or permanent retention, and appreciation of other
skills demanded by current competency-based paradigms such as learner centeredness, group dynamics and ill-defined problem solving.

Because of students’ positive opinions in the survey, the likelihood of type II error in the cognitive data cannot be overlooked i.e. that the conceptual assessments cannot establish a difference that actually exists. On the other hand type I error occurs when the test identifies a difference that does not exist. The probabilities of making these errors can be reduced by increasing the statistical power of the test such as by increasing sample size beyond the 19 for either group by involving participants from other institutions or other disciplines that have FMHT in their curricula.

Power analysis with inputs such as the kind of data tests to be used, the expected effect size and the allowable error rate, can be done prior to future experiments to determine appropriate sample size needed to obtain usually-reported effect size in studies of this nature.

Acknowledgments

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References


CHAPTER FIVE

Flow in helical channels with periodic slip and no-slip boundaries

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Drag reduction for liquid flow in channels is known to be enhanced by a combination of wall structure and hydrophobicity. This combination leads to trapping of air and essentially shear-free patches along the wall. The effective slip at the wall is enhanced not only by a large fraction of slip wall but also by the size of the slip regions relative to the hydraulic radius of the channel. A practical realization of a structure with alternating transverse strips of slip and no-slip boundary that can give relatively large slip-wall fractions and a large ratio of the length of the slip sections to tube radius is a cylindrical capillary channel supported by a stretched helical-wire spring with a hydrophobic coating. Some aspects of the flow in such a channel can be approximated by flow in the corresponding axisymmetric geometry of an array of wire rings. Flow in such a channel is modeled by the finite element method on a periodic domain obtained by matching velocity fields at the inlet and outlet of a period (separation between two consecutive slip boundaries or two consecutive no-slip boundaries). Drag reduction is found to increase with increasing pitch of the structure which increases the fraction of slip boundary, and to decrease with increasing roughness of the composite wire-plus-meniscus boundary and Reynolds number above 50. The fraction of slip boundary is increased in proportion to the pitch and also increases with increasing contact angle. Boundary roughness depends on contact angle, wire radius and the channel pressure that in turn affects the meniscus curvature. Inertial effects become more pronounced above a Reynolds number of 50. The highest drag reduction is found to occur for the highest contact angle, Reynolds numbers below 50 and for a channel pressure that gives a smooth liquid-gas interface (no-shear boundary).

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I. INTRODUCTION

Generally speaking, drag reduction or boundary slip can be enhanced by increasing the flow boundary slip fraction (structures that trap air) of a mixed slip, no-slip surface, and reducing flow boundary roughness. The slip length parameter defined by Navier as the proportionality constant in the wall velocity-wall shear rate relation is shown below for a wall represented by SL

\[ w(SL) = -\lambda \left| \frac{dw(r)}{dr} \right|_{SL} \]  

(1)

It can be interpreted as shown in Fig. 1. A mix of no slip and perfect slip on a boundary will lead to partial slip on that boundary.

![Geometrical interpretation of the Navier slip length λ](image)

FIG. 1. Geometrical interpretation of the Navier slip length λ.

Also of importance is the orientation of the flow with respect to the boundary. For the same size of slip and no-slip fraction, flows aligned parallel with the composite boundaries will experience less pressure drag than flows aligned transversely or obliquely. This is due to less stagnation in the flow direction in the former case. Stagnation in the flow direction when there is a sudden change from slip to no-slip boundary causes more inertia. Most wall-bounded effective slip flow configurations of practical interest consist of fixed composite walls with periodic alternating slip and no-slip boundaries. The distance between two consecutive
slip or two consecutive no-slip boundaries is often termed the pitch and is a very important parameter in the design of such walls. For a fixed no-slip size, increasing the pitch is beneficial because this will automatically increase the slip fraction and decrease the number of stagnation zones over a fixed flow distance. Over the last few decades, a number of analytical, semi-analytical, numerical and experimental studies have focused on investigating the dynamics of fluid flow over different surface geometries with potential drag reduction. The alternating no-slip and slip surface architectures include: ridges and trenches, posts of different cross-sections and spaces between, meshes with holes of different cross-sections, cylindrical structures and, needle-like pillars and space between them. These surfaces have been variously described as hydrophobic ($\theta_c > 90^\circ$), ultrahydrophobic, or super hydrophobic ($\theta_c > 150^\circ$). The size of the contact angles will depend on the following factors: chemical properties, nanoscale and micro scale roughness on the solid boundary, and slip fraction of the surface. None of these factors have been found sufficient in isolation for creating large slip.$^{1-3}$ However, a careful design using a mix of these factors can produce significant slip or drag reduction. In addition to these, slip reduces with increase in Reynolds number.$^{4,5}$ Passive drag reduction using these engineered superhydrophobic surfaces is desirable for energy savings in many flow applications of technological significance, especially as the scale reduces to micro and nanometer levels (the pressure drop across the channel scales as the reciprocal of the fourth power of the hydraulic diameter, $\Delta P \propto 1/D^4$). These applications include micro and nano fluidics, pipe flows in larger fluidic networks, marine vessels moving through sea water, machinery, and most relevant to this work, microgravity fluidic applications such as liquid propellant management and phase separations. Analysis of flow over plates and through circular tubes with alternating no-slip and no-shear boundaries arranged parallel
and/or transverse to the flow direction was first carried out by Philips.\textsuperscript{6} Lauga and Stone\textsuperscript{7} extended this investigation by semi-analytically analyzing flows through circular tubes with periodic arrangement of no-slip and no-shear slots arranged parallel or transversely to the primary flow. In these analyses, a perfectly cylindrical interface was assumed, and the no-shear fraction and period varied. The theory suggests that what is important for achieving large slip is not only the fraction of the boundary that is slip, but also how that slip boundary is interspersed with the no-slip fraction of the boundary, in other words the pitch of the wall structures non-dimensionalized with respect to the channel diameter. In fact, the slip length was found to be proportional to the pitch in the case of transverse alternating strips of slip and no-slip boundary. Importantly, they also found that the slip was higher with longitudinally arrayed alternating strips compared to transverse arrays. For Stokes flow with transversely arrayed mixed no-slip no-shear smooth cylindrical boundaries, it was shown that the slip length, $\lambda$ normalized with respect to the pipe radius, $R$ scales as follows:

$$\frac{\lambda}{R} = \frac{L}{2\pi R} \ln(\sec(\frac{\delta \pi}{2}))$$

where $L$ is the dimensional pitch of the mixed perfect slip, no-slip boundary structure and $\delta$ is the area fraction of perfect-slip boundary. Equation 2 suggests that even for a small pitch a large smooth shear-free portion (for instance the case of a small wire radius) can still lead to a greater than zero effective slip. It would therefore be desirable to push the limits of $\delta$ and $L/R$ while maintaining a smooth boundary in order to achieve significant drag reduction. The length of free cylindrical liquid surfaces are however limited by capillary stability issues. For an infinite array of linked cylindrical capillary bridges (liquid bridging between two cylinders) each of length $L$, the stability limit is the same as for a fixed-pressure capillary bridge $L = \pi R$, one-half the circumference of the bridge. A comparison of finite volume
calculations for flows over staggered posts\textsuperscript{8} compared well with analytical solutions for the case of a solid no-slip boundary with random distribution of equal circular free-slip areas\textsuperscript{9} provided the slip fractions were the same in both cases. In practical flow situations, the slip boundary constitutes liquid-gas interface whose shape can deviate from planar or cylindrical due to a pressure jump across the interface in response to the local pressure in the channel. This deflection in the shape leads to surface roughness and reduces the effective boundary slip. Numerical analyses have quantified the reduction in slip due to this roughness\textsuperscript{8,10,11} and the associated extra form drag and change in velocity field caused by the interface roughness and change in flow cross-section, respectively. In addition, Sarkar and Prosperetti\textsuperscript{12} have shown that a surface with 100\% slip but with surface roughness can behave like a no-slip boundary, indicating further that a minimally rough boundary is desirable for large slip.

In the present study we consider slip behavior in fully developed capillary flow in a stretched spring geometry approximated as a periodic array of circular wires bridged by a liquid meniscus similar to the Lauga and Stone geometry\textsuperscript{7}. This spring geometry represents a convenient way to achieve large slip fraction as the the spring can be simply stretched to increase the pitch. In addition, making the spring non-wetting can increase the stable positive pressure range that it can hold. The slip fraction will increase with increase in pitch and contact angle (non-wetting), and decrease in the size of the no-slip boundary. On the other hand, the boundary roughness increases with increase/decrease in channel pressure, decrease in contact angle, and other structures that may protrude into the flow. This work extends the Cassie state boundaries (smooth liquid-air interface) studied by Lauga and Stone\textsuperscript{7}, and the Wenzel states (rough liquid-air interface) explored by Ng and Wang\textsuperscript{10} by exploring states similar to Cassie using very high contact angles and channel pressures.
that give cylindrical menisci, and states similar to Wenzel by using rough boundaries (wire penetration, bulged-out or sucked-in liquid-gas interface). Periodic boundary, finite element solution of the two-dimensional Navier-Stokes equation was done on one repeating unit of the geometry. The slip length was calculated as a function of the following dimensionless parameters: contact angle, wire radius, pitch, Reynolds number and Laplace pressure. The finite element model was validated by reproducing results for closely related geometries that have semi-analytical solutions\textsuperscript{7,10} (Fig. 4).

II. MODEL

A. Geometry

The geometry to be modeled consists of an array of concentric wire rings with a liquid bridging from ring to ring with a possibly axially curved meniscus. For the sake of simplicity the meniscus shapes are approximated as sections of toroids. This is only an approximation to the free surface shape and does not have constant mean curvature as required for an equilibrium capillary surface, however, for the purposes of flow modeling, this will suffice. Computations are carried out for both fully-developed flow and for flow development. For the case of fully-developed flow we can take advantage of the periodic geometry and solve the problem on one unit cell with periodic boundary conditions. The periodic geometry is shown in Fig. 2, indicating the geometric parameters of the support structure made dimensionless by the ring radius $R$, including the wire radius, $r_w$, and pitch $L$, and the geometric parameters for the shape of the meniscus including the radius of axial curvature, $r_m$, and the center of axial curvature, $r_{mc}$. The free-surface shape assumed here approximates a capillary pressure that is dependent on the interfacial tension $\sigma$ and is proportional to twice the mean curvature.
The geometry is non-dimensionalized with respect to the radius of the coil to the center of the wire, $R_c$. Within the periodic computational domain the center of the wire is located at $(r=1, z=0)$ and the dimensionless wire radius is $r_w$. The parametric representation of points on the submerged wire boundary is then:

$$r = 1 - r_w \cos(s) \quad z = r_w \sin(s) \quad -s_w < s < s_w$$

The model geometry is specified parametrically in terms of an arc angle $s$. The parametric representation of points on the meniscus is:

$$r = r_{mc} + r_m \cos(s) \quad z = \pm \frac{L}{2} \mp r_m \sin(s) \quad 0 \leq s \leq s_m$$

and of the immersed boundary of the wire

$$r = 1 - r_w \cos(s) \quad z = \pm r_w \sin(s) \quad 0 \leq s \leq s_w$$

The arc lengths $s_m$ and $s_w$ must be found for the intersection of the meniscus arcs with the wire in order to specify the contact angle. The geometric parameters of the free surface, $r_m$, $r_{mc}$, $s_m$, and $s_w$ can be determined by specifying the contact angle on the wire and the capillary pressure as shown in Appendix A, Eqs. A2 and A3.

B. Governing equations

The Navier-Stokes equations for steady axisymmetric flow in the absence of a body force are

$$\rho \left( u \frac{\partial u}{\partial r} + w \frac{\partial u}{\partial z} \right) = -\frac{\partial p}{\partial r} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial u}{\partial r} \right) + \frac{\partial^2 u}{\partial z^2} - \frac{u}{r^2} \right]$$

$$\Delta P_{interface} = \sigma 2M = \sigma \left[ \frac{1}{r_m} + \frac{1}{(r_m + r_{mc})} \right]$$
FIG. 2. (a) Periodic array of wires bridged by a meniscus. The parameters in the figure are dimensionless. \( L' \) is the pitch, \( \theta_c \) is the contact angle and \( \theta_w \) fixes the position of the meniscus on the wire (pinned contact line position), \( R' \) is the channel inner radius normalized by the coil radius \( R_c \), \( R'_c \) is the coil radius (distance from channel center to wire center), and \( r_w \) is the wire radius. 

(b) The periodic boundary (PB) condition computational domain for liquid that bridges an array of wire rings.

\[
\rho \left( u \frac{\partial w}{\partial r} + w \frac{\partial w}{\partial z} \right) = -\frac{\partial p}{\partial z} + \mu \left[ \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial w}{\partial r} \right) + \frac{\partial^2 w}{\partial z^2} \right] \tag{5}
\]

\[
\frac{1}{r} \frac{\partial}{\partial r} (ru) + \frac{\partial w}{\partial z} = 0 \tag{6}
\]

where \( \mu \) is the fluid viscosity, \( \rho \) is the fluid density, \((r, z)\) are the radial and axial coordinates, \((u, w)\) are the radial and axial velocity components and \( p \) is the pressure. The pressure will be written in terms of a mean axial gradient plus a disturbance

\[
p = -z \left| \frac{dP}{dz} \right| + \tilde{p}
\]
Defining a length scale as the coil radius $R_c$, velocity scale as the mean velocity for pressure-driven flow in a smooth tube of radius $R$

$$U_{scale} = R^2 \left| \frac{dP}{dz} \right| \frac{1}{8\mu}$$

The pressure scale is:

$$p_{scale} = R_c \left| \frac{dP}{dz} \right|$$

Non-dimensionalizing the velocities by a velocity scale $U_{scale}$, lengths by $R_c$, and pressure by $p_{scale}$, multiplying the radial and axial momentum equations by $R_c^2/\mu U_{scale}$ and substituting for the pressure gives

$$\frac{\rho U_{scale} R_c}{\mu} \left( u' \frac{\partial u'}{\partial r'} + w' \frac{\partial u'}{\partial z'} \right) = -\frac{p_{scale} R_c}{\mu U_{scale}} \frac{\partial \tilde{p}'}{\partial r'} + \left[ \frac{1}{r'} \frac{\partial}{\partial r'} \left( r' \frac{\partial u'}{\partial r'} \right) + \frac{\partial^2 u'}{\partial z'^2} - \frac{u'}{r'^2} \right]$$  \hspace{1cm} (7)

$$\frac{\rho U_{scale} R_c}{\mu} \left( u' \frac{\partial w'}{\partial r'} + w' \frac{\partial w'}{\partial z'} \right) = -\frac{p_{scale} R_c}{\mu U_{scale}} \frac{\partial \tilde{p}'}{\partial z'} + \left[ \frac{1}{r'} \frac{\partial}{\partial r'} \left( r' \frac{\partial w'}{\partial r'} \right) + \frac{\partial^2 w'}{\partial z'^2} \right] + \frac{R_c^2}{\mu U_{scale}} \left| \frac{dP}{dz} \right|$$  \hspace{1cm} (8)

Substituting

$$U_{scale} = \frac{R^2 \left| \frac{dP}{dz} \right|}{8\mu}$$

in the pressure term and solving and then manipulating the coefficient of the inertial term on the left hand side. The dimensionless Navier-Stokes equations are then

$$\frac{\text{Re}_c R_c}{2R} \left( u' \frac{\partial u'}{\partial r'} + w' \frac{\partial u'}{\partial z'} \right) = -8 \left( \frac{R_c}{R} \right)^2 \frac{\partial \tilde{p}'}{\partial r'} + \left[ \frac{1}{r'} \frac{\partial}{\partial r'} \left( r' \frac{\partial u'}{\partial r'} \right) + \frac{\partial^2 u'}{\partial z'^2} - \frac{u'}{r'^2} \right]$$  \hspace{1cm} (9)

$$\frac{\text{Re}_c R_c}{2R} \left( u' \frac{\partial w'}{\partial r'} + w' \frac{\partial w'}{\partial z'} \right) = -8 \left( \frac{R_c}{R} \right)^2 \frac{\partial \tilde{p}'}{\partial z'} + \left[ \frac{1}{r'} \frac{\partial}{\partial r'} \left( r' \frac{\partial w'}{\partial r'} \right) + \frac{\partial^2 w'}{\partial z'^2} \right] + 8 \left( \frac{R_c}{R} \right)^2$$  \hspace{1cm} (10)

$$\frac{1}{r'} \frac{\partial}{\partial r'} (r' u') + \frac{\partial w'}{\partial z'} = 0$$  \hspace{1cm} (11)
where the primes indicate dimensionless quantities normalized with the appropriate scaling factors and the parameter $Re_s$ is given by

$$Re_s = \frac{\rho U_{\text{scale}} 2R}{\mu}$$

We can postulate that the velocity profile can be represented thus

$$w = w_o \left( 1 - c \left( \frac{r}{R} \right)^2 \right)$$  \hspace{1cm} (12)

For Poiseuille flow, $c = 1$ and for finite slip at the wall $c \neq 1$ For effective slip on the boundary, the flow rate is obtained by integrating the velocity profile over an element of the cross-section:

$$\dot{V} = 2\pi w_o \int_0^R \left( 1 - c \left( \frac{r}{R} \right)^2 \right) r dr = \pi w_o R^2 \left( 1 - \frac{c}{2} \right)$$  \hspace{1cm} (13)

The Reynolds number as a consequence of the effective boundary slip is obtained from the solution of the alternating slip, no-slip model. This Reynolds number will therefore be a function of any parameter which influences the boundary slip (i.e. wetting, interface roughness, wire radius, and pitch).

$$Re = \frac{2\rho \bar{w} R}{\mu}$$  \hspace{1cm} (14)

where $\bar{w}$ is the mean velocity in the channel based on the cross-sectional area $\pi R^2$

$$\bar{w} = \frac{\dot{V}}{\pi R^2} = \frac{\dot{V}'}{\pi R^2 U_{\text{scale}}}$$  \hspace{1cm} (15)

where $\dot{V}'$ is the dimensionless volumetric flow rate from the full geometry model. Because of the alternating slip and no-slip boundary, we can characterize the flow in the channel in terms of an effective slip length $\lambda_{eff}$ that is defined such that a smooth cylindrical conduit of radius $R = R_c - r_w$ with a partial-slip boundary condition and the same pressure gradient as the real channel, has the same flow rate $\dot{V}$. By a force balance on a section of the pipe,
for a given pressure gradient and fluid properties, the wall stress must be invariant as the
slip parameter changes

\[ \frac{\partial w}{\partial r} \bigg|_R = -2c \frac{w_0}{R} \]  

(16)

According to Navier’s hypothesis, the non-zero slip velocity at the wall (the boundary con-
dition at an effective slip boundary) is proportional to the shear rate at the wall, the propor-
tionality constant being the slip length, \( \lambda_{eff} \)

\[ w(r = R) = -\lambda_{eff} \left. \frac{dw}{dr} \right|_{r=R} \]  

(17)

From Eq. 17

\[ \frac{\partial w}{\partial r} \bigg|_R = -w_0 \frac{1}{\lambda_{eff}} \left( 1 - c \right) \]  

(18)

Equating Eq. 16 and 18 gives

\[ c = \frac{R}{2\lambda_{eff} + R} \]  

(19)

For a no-slip boundary \( c = 1 \) and \( \bar{V} = \pi R^2 \bar{w} \) and we can equate this to Eq. 13 for \( c = 1 \)

\[ \frac{\pi w_0 R^2}{2} = \pi R^2 \bar{w} \]

from whence

\[ w_0 = 2 \bar{w} \]

and

\[ w = 2 \bar{w} \left( 1 - \left( \frac{r}{R} \right)^2 \right) \]

\[ \frac{\partial w}{\partial r} \bigg|_R = -4 \frac{\bar{w}}{R} \]  

(20)

Equate Eq. 18 and Eq. 20

\[ w_0 = 4 \bar{w} \frac{\lambda_{eff}}{R(1-c)} = 4 \bar{w} \frac{2\lambda_{eff} + R}{2R} \]  

(21)
\[ \pi w_0 R^2 \left( 1 - \frac{c}{2} \right) = \pi w_0 R^2 \left( \frac{4\lambda_{eff} + R}{2(2\lambda_{eff} + R)} \right) \]  

(22)

but

\[ w_0 = 2\bar{w} \frac{2\lambda_{eff} + R}{R} \]

This simplifies to

\[ \frac{\dot{V}}{\pi \bar{w} R^2} - 1 = 4 \frac{\lambda_{eff}}{R} \]  

(23)

substituting \( w_0 = 2\bar{w} \) into Eq. 23 we have

\[ \frac{\dot{V}}{2\pi w_0 R^2} - \frac{1}{4} = \frac{\lambda_{eff}}{R} \]  

(24)

\[ \left| \frac{dP}{dz} \right| \] is the constant axial pressure gradient in a pipe with radius \( R \)

\[ \left| \frac{dP}{dz} \right| = \frac{2\rho f \bar{w}^2}{2R} = \frac{2\bar{w}^2}{2R} \frac{16}{Re} = \frac{8\mu \bar{w}}{R^2} \]  

(25)

from Eq. 25

\[ w_0 = 2\bar{w} = R^2 \left| \frac{dP}{dz} \right| \frac{1}{4\mu} \]

\[ \frac{\lambda_{eff}}{R} = \frac{\dot{V}}{2\pi R^2 w_0} - \frac{1}{4} = \frac{2\mu \dot{V}}{\pi R^4 \left| \frac{dP}{dz} \right|} - \frac{1}{4} \]  

(26)

The volumetric flow rate scale is

\[ \dot{V}_{scale} = R_c^2 U_{scale} = R_c^2 \left( \frac{dP}{dz} \right) \frac{R_c^2}{8\mu} \]

Such that

\[ \dot{V} = \dot{V}_{scale} \dot{V}' \]

Thus we have

\[ \frac{\lambda_{eff}}{R} = \frac{1}{4} \left[ \left( \frac{R_c}{R} \right)^2 \frac{\dot{V}'}{\pi} - 1 \right] \]  

(27)
By rearranging Eq. 26, the pressure gradient required to drive flow at a given flow rate and slip length is

$$\left| \frac{dP}{dz} \right| = \frac{2\mu \dot{V}}{\pi R^4 \left( \frac{\lambda_{eff}}{R} + \frac{1}{4} \right)}$$  \hspace{1cm} (28)

By a force balance on the channel, the pressure gradient is the quotient of the total drag force on the boundary and the channel volume:

$$\left| \frac{dP}{dz} \right| = \frac{2\mu \dot{V}}{\pi R^4 \left( \frac{\lambda_{eff}}{R} + \frac{1}{4} \right)} = \frac{F_{\text{drag}}}{\pi R^2 L}$$  \hspace{1cm} (29)

so that,

$$\frac{2\mu \ddot{w}}{R^2 \left( \frac{\lambda_{eff}}{R} + \frac{1}{4} \right)} = \frac{F_{\text{drag}}}{\pi R^2 L}$$  \hspace{1cm} (30)

Substituting for $Re$ we have:

$$\frac{2\mu^2 Re}{\rho R^3 \left( \frac{\lambda_{eff}}{R} + \frac{1}{4} \right)} = \frac{F_{\text{drag}}}{\pi R^2 L}$$

$$\left[ \frac{\pi \mu^2 L}{\rho R \left( \frac{\lambda_{eff}}{R} + \frac{1}{4} \right)} \right] Re = F_{\text{drag}}$$

We can postulate that the drag force on the boundary, which is inversely related to the slip length, will have the following Reynolds number functionality:

$$F_{\text{drag}} = aRe + kRe^2$$  \hspace{1cm} (31)

since the pressure gradient scales as velocity to the first power in laminar flow and as velocity to the second power for turbulent flow. The first term represents the viscous component, the second term the inertial component, and $a$ and $k$ are constants to be determined for the particular case of interest. Because of the mixed flow boundary there will always be inertial effects even at Reynolds numbers below turbulence. This will of course be increased with Reynolds number. Comparing coefficients:

$$\frac{\pi \mu^2 L}{\rho R \left( \frac{\lambda_{eff}}{R} + \frac{1}{4} \right)} = a$$
Hence, comparing to the Lauga and Stone scaling of Eq. 2:

\[
\frac{\lambda_{\text{eff}}}{R} = \frac{\pi \mu^2 L}{\rho R a} - \frac{1}{4} = \frac{L}{2\pi} \ln(\sec(\frac{\delta \pi}{2}))
\]  

(32)

From whence

\[
a = \frac{\pi \mu^2 L}{\rho R [\frac{L}{2\pi} \ln(\sec(\frac{\delta \pi}{2})) + \frac{1}{4}]}
\]

\[
\frac{\lambda_{\text{eff}}}{R} = \frac{\frac{L}{2\pi} \ln[\sec(\frac{\delta \pi}{2})] + \frac{1}{4}}{1 + a Re} - \frac{1}{4}
\]  

(33)

For Stokes flow, \( Re \to 0 \), this reduces to the Lauga and Stone scaling, Eq. 2. and for infinitely high Reynolds number, the slip length (Eq. 33) degrades to -1/4.

C. Model validation

To validate the finite element model we compare computed results for simpler geometries that have semi-analytical solutions in the Stokes-flow limit. In particular we compared to the case of a smooth tube with alternating slip and no-slip boundary (see Fig. geomschemes (a)) and to the case of a cylindrical channel with periodic grooves coupled with alternating slip and no-slip boundary. The general periodic domains are shown in Fig. 3. The validation results are shown in Fig. 4. A comparison of the finite element model with results from the model of Lauga and Stone is shown in Fig. 4 (a). Our numerically calculated slip lengths (plus signs) for a Stokes flow transverse to periodic shear-free patterns arranged axially along the pipe and for a period of 1, agrees quite well with the theory (closed circles) and scaling (line) represented by Eq. 2, which is Eq. A27 in that publication. Lauga and Stone had earlier proposed the following scaling for the limit where the slip fraction goes to 100% for
FIG. 3. Schematics illustrating the front views of the computational geometries: (a) Lauga and Stone alternating slip, no-slip cylinder, (b) Ng and Wang alternating slip, no-slip with grooves and (c) geometry used in the present study.

Stokes flow transverse to the boundary (Eq. A25 of their paper)

$$\frac{\lambda_{\text{eff}}}{R} = \frac{1}{4(1 - \delta)} \lim_{\delta \to 1}$$

(34)

This scaling (Eq. 34) predicts that the slip length approaches infinity in the limit of large slip fraction and a corresponding numerical result (Fig. 3(a) of that work) shows the same trend
FIG. 4. (a) Theory, FEM, and scaling results for the Lauga and Stone\(^7\) geometry for Stokes flow and a period of 1. Here, \(\delta\) refers to the slip fraction and \(1-\delta\) to the no-slip fraction. (b) Theory and FEM results for Stokes flow in the Ng and Wang\(^{10}\) geometry for the radius of the no-slip region \(R=1\) for slip fraction \(a=0.9\) (see Fig. 3 of that work). Here, \(b\) refers to the boundary roughness (groove depth or peak-to-peak roughness).

for large amount of slip. However, our implementation of the same solution in finite elements and an independent implementation of their series solution revealed a premature truncation of the series solution on their part (i.e. there were not enough terms for adequate resolution of the flow field on the vanishing no-slip boundary in their numerical solution). It turns out that the correct scaling is Eq. 2 since all the sinusoidal terms \((\sin(n\pi\delta))\) in Eq. A24 of their work do not all vanish as the number of terms \(n\) becomes very large. Incidentally, this is the scaling they proposed for the limit of small distance between slip regions (small period). The scaling appears valid for both the small and moderate period cases. As a further validation of the finite element model, since we proposed to study the effect of boundary roughness in our model, we implemented a finite element numerical solution of Stokes flow through a
cylindrical conduit with periodic slip grooves (Fig. 3 (b)) of different depth or roughness and compared the results to the series solution of the same problem. Fig. 4 (b) shows the comparison of the results for a radius of no-slip region of 1 and a slip fraction of 0.9. The comparison shows very good agreement. Our independent solution of the series solutions using a large number of terms N=200, showed good agreement with the solution of Ng and Wang (Fig. 3 of that work).

III. RESULTS AND DISCUSSION

A. Effect of slip fraction

The fraction of flow boundary that is slip will depend on pitch, wire radius and contact angle. To increase the slip fraction, it is necessary to increase the pitch and contact angle and reduce the size of the wire. Because of the small wire sizes used in this work, the dominant determinant for slip fraction would be the pitch. The effects of wire radius, contact angle and pitch on slip length are shown in Figs. 5, 6 and 7 respectively. The dimensionless slip length is calculated using the solution from the finite element model by Eq. 27. The effect of wire radius for a fixed pitch of 0.5, a contact angle of 178°, and a cylindrical meniscus is shown in Fig. 5. The slip length is seen to increase with decreasing wire radius. For the same contact angle, pitch and channel pressure, a larger radius translates to a larger fraction of the boundary being no-slip and thus to a reduced slip length according to the Lauga and Stone scaling, Eq. 2. Also, the nonuniform increase in normalized slip length as the normalized wire radii are decreased in uniform amounts of 0.04, suggest that the drag reduction is not only due to viscous dissipation occasioned by increase in solid fraction but also a reduction in hydraulic radius as the radius increases because there is more solid protrusion into the flow.
Furthermore, Ng and Wang’s \textsuperscript{10} dimensionless slip length result for a cylindrical meniscus (\( b=0 \)) and channel radius \( R = 1 \) for a high no-shear fraction (90\%) are in close agreement with the slip length obtained for a wire radius \( r_w = 0.02 \) and a corresponding no-shear fraction of about 98.5\% (0.54 Fig. 2 of Ng and Wang\textsuperscript{10} vs. 0.50, Fig. 5, this work). Even though the slip fraction is higher for our case and so we should expect a higher slip, form drag appears to dominate the total drag due to the wire curvature hence the reduced effective slip. While the slip trend shown in Fig. 5 makes it more attractive to use the smallest wire radius available, mechanical integrity, especially under normal gravity, govern the choice of wire for practical applications. The effect of contact angle on effective slip is shown in Fig. 6. For contact angles of 2\(^\circ\) and 46\(^\circ\), the effective slips are not distinguishable. It is expected that slip be enhanced for 46\(^\circ\) over 2\(^\circ\) because of the smaller no-slip fraction in the former but apparently the difference in no-slip fraction does not translate into measurable slip difference probably because the pressure drag due to the wire intrusion into the flow still strongly dominates the overall drag at 46\(^\circ\). Also the difference between the highly wetting cases and the neutral wetting (\( \theta_c=90^\circ \)) case is slight which further suggests that the slip for wetting angles are similar at the same Laplace pressure. As the the contact angle is increased beyond neutral wetting to hydrophobia (134\(^\circ\)), an 80\% jump in slip length is observed. This is attributable to reduced solid fraction which leads to both reduced viscous and pressure drag respectively. The drag reduction would be more due to the reduced intrusion into the flow because the wire radius was small to begin with and so the viscous drag will be less. As extreme superhydrophobia is reached (\( \theta_c=178^\circ \)) another sudden jump in slip of about 90\% is observed. This is due to a drastic reduction in fluid-solid contact area and an almost total elimination of wire intrusion into the fluid. At this contact angle and this Laplace pressure
the fluid is mostly gliding on a cushion of air.

![Graph](image)

**FIG. 5.** The variation in effective slip with wire radius. The wire radii are in the commercially available range. The dimensionless pitch is 0.5, the contact angle $\theta_c$ is $178^\circ$, the Laplace pressure is 1.1 to give a cylindrical meniscus. The Laplace pressure was set in the model by setting $\theta_w$ to be slightly greater than $(\pi - \theta_c)$.

The effect of pitch on slip for a highly non-wetting case ($178^\circ$) is seen in Fig. 7. The slip length scales approximately linearly with pitch in this case as predicted by Lauga and Stone$^7$ and increases monotonously with increase in pitch. The small-pitch scaling given by Lauga and Stone is:

$$\frac{\lambda_{eff}}{R} \sim \frac{L}{2\pi} \ln \left( \sec \left( \frac{\pi}{2} \right) \right) \quad (\lim L \to 0) \quad (35)$$
FIG. 6. The variation in effective slip with contact angle (wetting condition). The contact angles range from highly wetting ($\theta_c < 90^\circ$) through neutral wetting ($90^\circ$) to highly non-wetting ($\theta_c > 90^\circ$). The dimensionless pitch is 0.5, the dimensionless wire radius is 0.1 and the interface is cylindrical.

For our geometry, and a flat interface, $\delta$ can be approximated as follows:

$$\delta = \frac{L - 2R_w \sin(\pi - \theta_c)}{L}$$

Note that the model agrees reasonably well with the scaling under Stokes flow conditions ($Re = 0.001$) and only at low pitch for Reynolds number much greater than zero and diverges for larger pitches. The model and scaling diverge as wetting increases because of the penetration of the wire into the liquid which deviates from the Cassie state assumed in

\[183\]
the Lauga and Stone scaling\textsuperscript{7}. These results are also qualitatively consistent with the highly linear relationship between slip length and pattern width (pitch) for square posts obtained by Cheng, Theo and Khoo\textsuperscript{4}. The same study also found that the slip length increased with pitch for square holes, transverse and longitudinal grooves.

FIG. 7. (a) The variation in effective slip with pitch. The contact angle is $178^\circ$, Re = 1e-5 and 1000 for the upper dashed lines and the lower dotted lines respectively, and the dimensionless Laplace pressure is around 1.1, giving a nearly cylindrical meniscus. The Laplace pressure was set in the model by setting $\theta_w = 0.035$ (approximately $\pi - \theta_c$). (b) Dimensionless slip length as a function of pitch for $\theta_c=178^\circ$, 134\degree and 90\degree, $R_w = 0.1$, $Re = 1e - 5$ and cylindrical meniscus, compared to the Lauga and Stone scaling. The solid lines on top of the curves identified in the legend represent the scaling from Eq. 2.

B. Effect of roughness

The effect of flow boundary roughness can degrade or enhance boundary slip depending on the particular situation\textsuperscript{13,14}. Vinogradova and Belyaev’s review\textsuperscript{13} highlight the complexity
of the effects of boundary roughness. The general consensus is that if the rough surface is hydrophobic and traps air, the so-called fakir or Cassie state, it is more likely to enhance slip. Another view is that the slip reported depends on the location of the reference boundary with respect to the roughness\(^\text{14}\). For the mixed-boundary flows in our case, the boundary roughness generally increases with liquid-gas interface curvature which is determined by the Laplace pressure (which implies channel pressure), a more wetting solid boundary and a larger wire radius. The interface can be sucked-in, bulged-out or perfectly cylindrical depending on the difference between the channel pressure and the ambient pressure. In addition, when the solid boundary is more wetting and as wire radius is increased, the wire protrudes more into the flow introducing an additional source of both viscous and pressure drag. Also, the larger the pitch the more likely it is for the interface to bulge out as pressure is increased i.e. compliance increases with increase in slip fraction. The effect of the first three sources of roughness will be discussed separately in light of relevant literature and then integrated. The effective slip for flow in the channels is strongly dependent on the free-surface curvature that in turn is dictated by the local pressure in the channel (Eq. 3). For a dimensionless wire radius of 0.1 and for the Stokes flow regime, the effective slip as a function of the Laplace pressure for different contact angles and different pitches is shown in Fig. 8. It can be seen that the greatest slip occurs when the fluid is most non-wetting and that there is typically a maximum slip with respect to pressure. For the general case, as pressure is reduced or increased, there are competing effects that influence the slip. On the one hand as the meniscus is sucked in there is less solid in contact with liquid and that solid is more shielded from the core of the flow and creates cavities in which the fluid is essentially stagnant. This causes the boundary between the core flow and the cavity to
behave nearly like a no-slip boundary. A related classical fluid mechanics problem is the lid-driven cavity. At low Reynolds number the shear stress on the lid of the lid-driven cavity is proportional to the tangential velocity of the lid and is proportional to a higher power of this velocity at high Reynolds numbers. The lid shear stress for a unit aspect ratio cavity is nearly independent of whether the bottom surface of the cavity is slip or no-slip. This stagnation might be expected to lead to less slip. On the other hand the cross-sectional area for flow is constricted leading to larger velocity gradients, and thus reduced slip. As pressure is increased in the case of bulged-out meniscus, there is also the presence of cavities in which the fluid is stagnant which will lead to less slip. Also, the cross-section for flow is greater which may lead to smaller velocity gradients and may increase slip. Thus a combination of these effects will determine the magnitude of the measured slip. For fixed Reynolds number, contact angle, pitch and wire radius, the slip will therefore be expected to be maximum at a particular channel pressure (which will depend on the contact angle, and pitch) that makes the meniscus and the channel have an effective smoothness (i.e. minimal liquid-air interface roughness) and minimal stagnation. This dimensionless channel pressure would depend also on how non-wetting or wetting the substrate is. For the most non-wetting case (178° contact angle), Fig. 8 (a), the slip length is observed to increase generally with pitch and to peak at about a Laplace pressure of 1.1 for pitches from 0.5 to 1. It can also be observed that the slip length drops off faster for larger pitches as the pressure is increased. This is attributable to higher compliance as the pitch is increased\textsuperscript{15} which leads to more bulge and deeper stagnation cavities. This same trend is seen for the other contact angles in Fig. 8 (b)-(d). Also, for all the contact angles studied, at the smallest pitch, very minimal slip length is observed even at much higher pressures than for the larger pitches. At this
pitch, the channel behavior is close to pipe-like. It is also observed that for the smallest pitch of 0.25, the slip length stays constant even as the Laplace pressure is raised suggesting a competition between the increasing effective flow cross section and the increasing stagnation zones as the size of the cavity increases. It is noticed from Fig. 8 (b) to (e) that as the contact angle decreases below 178°, the point of maximum slip moves further away from the pressure corresponding to a cylindrical meniscus suggesting that some roughness may be beneficial to slip enhancement in these cases\textsuperscript{13,14}. Note also that for the last 3 cases (Fig. 8 (c),(d), and (e)) at a pitch of 0.25, the slip lengths are invariant and consistently less than 2% of the coil radius (almost vanishing) strongly suggesting closed pipe behavior at such a small pitch. For the hydrophobic case Fig. 8 (b), the slip length drops down to 2% and becomes invariant after 0 pressure indicating that even for a hydrophobic surface a large pitch is still required for appreciable slip. Finally, the superhydrophobic case (Fig. 8 (a)) shows similar pipe-like behavior at a pitch of 0.25 but from a normalized pressure of 4 and above it is very close to zero indicating that even with superhydrophobia at a low pitch and high interface roughness the slip behavior degrades to pipe-like boundary conditions. A comparison of our plots of slip as a function of Laplace pressure with the results in Fig. 3 of Ng and Wang\textsuperscript{10} reveals a qualitative agreement between Fig. 8 (e) and their curves for $R = 1.0$ and slip fractions $a = 0.3$ and 0.5.

Fig. 9 shows a plot of slip length as a function of peak-to-peak roughness for our model and the Ng and Wang\textsuperscript{10} for similar conditions. The computational parameters for our model are: $R' = 1$, $r_w = 0.1$ (equivalent to no-slip fraction $c = 0.1$ for the Ng and Wang case\textsuperscript{10}), $L' = 2$ and cylindrical liquid-gas interface similar to the conditions for one of the graphs in Fig. 3 of Ng and Wang\textsuperscript{10} ($L/2 = 1$, $a = 0.9$ and $c = 0.1$). For both models the roughness
FIG. 8. Slip length as a function of Laplace pressure for different pitches and different contact angles. The wire diameter is 0.1 for all cases (a) $\theta_c = 178^\circ$ (b) $\theta_c = 134^\circ$ (c) $\theta_c = 90^\circ$ (d) $\theta_c = 46^\circ$ (e) $\theta_c = 2^\circ$.

protrudes into the fluid with the one difference been that in the Ng and Wang model the roughness is rectangular while in our case it is cylindrical. Because the wire protruding
FIG. 9. Slip length as a function of peak-to-peak boundary roughness for Stokes flow for the present geometry (solid line) and the Ng and Wang geometry (squares). The parameters for our FEM model are $Re = 10^{-7}$, $L' = 2$, $r_w = 0.1$ and cylindrical meniscus for various $\theta_c$. The parameters for our FEM model are $Re = 10^{-7}$, $L' = 2$, $r_w = 0.1$ and cylindrical meniscus for various $\theta_c$. into the flow in our case is curved (Fig. 3), the roughness for our model will taken to be the maximum radial distance form the smooth liquid-gas interface to the edge of the wire penetrating into the fluid, while that in the Ng and Wang model is the penetration of the groove into the primary flow. This distance will be inversely proportional to the contact angle in our case i.e. the roughness will decrease with increase in contact angle. It is evident from Fig. 9 that even though there is some qualitative agreement between the two models, the slip for our model (solid line) is consistently higher than the slip from the Ng and Wang model (squares). This is partly because, in the latter model the edge protruding into the flow is abrupt and will cause more flow separation and recirculation behind the edges. For our case, the protruding wire will not cause as much separation because of the gradually
sloping edge of the wire. Also, as the roughness decreases with increasing contact angle in the case of the wire bridge geometry (see Fig. 3 (c)), the hydraulic radius increases and the no-slip fraction decreases to the point where the fluid is almost floating on air, which leads to a large increase in slip. However for the groove geometry (Fig. 3 (b), even though the hydraulic radius increases with decrease in roughness, the no-slip boundary remains the same and consequently there is not as large an increase in slip.

C. Effect of Reynolds number

The effect of Reynolds number is seen in Fig. 5 for different wire radii, a pitch of 0.5, a 170° and a flat interface and also in Fig. 6. Effective slip is seen to be independent of Reynolds number below Reynolds numbers of around 50 (viscous dominated Poiseuille flow). Beyond this $Re$, the effective slip starts dipping gradually as inertial contributions to the momentum equations increase. This fluid inertia, which is ubiquitous because of the mixed boundary, is caused by the mixed boundary (slip and no-slip) causing streamlines to be straighter near the slip boundary and less so over the wires and causing elevated shear at the wires. The flow undergoes spatially periodic accelerations and decelerations at the edges of the periodic solid wires which are transverse to the flow direction and thus the slip length starts to exhibit dependence on the Reynolds number. This result is consistent with that obtained by Cheng and co-workers\textsuperscript{4} where a similar trend was predicted for square posts, square holes and transverse grooves in a rectangular confined channel. It is noteworthy to state that their simulations found no Reynolds number effect for grooves longitudinal to the flow because of the absence of nonlinear convective acceleration terms in the momentum equation for this case.
D. Flow fields and pressure perturbations

The streamline and perturbation pressure fields for the case of a relatively smooth boundary and a rough boundary are shown in Fig. 10 and Fig. 11, respectively. Because

![Fig. 10](image1.png)

**FIG. 10.** Streamlines (a) and the corresponding perturbation pressure field (b) for $Re = 1159$, $p = 1.1$ and $\theta_c = 150^\circ$. In (a), the interface is seen to correspond with the stagnation streamline. In (b), a large positive stagnation pressure is seen at the upstream contact line and a large negative stagnation pressure at the downstream contact line.

![Fig. 11](image2.png)

**FIG. 11.** Streamlines (a) and the corresponding perturbation pressure field (b) for $Re = 1074$, $p = 4.3$ and $\theta_c = 120^\circ$. In (a), the stagnation streamline is seen to be separated from the contact line and a recirculation zone is seen between the wires. In (b), the peak stagnation pressures are found to be well separated from the contact lines and are of smaller magnitude than for the smooth boundary case of Fig. 10.

we have assumed that the interface is not affected significantly by the dynamic pressure
disturbances it is necessary to compare the peak dynamic pressure perturbations along the free surface to the Laplace pressure of the meniscus. For the smoother boundary shown in Fig. 10, the dimensionless perturbation pressure ranges from -3.7 downstream to 7.3 upstream while for the rougher boundary Fig. 11, the range is -1.45 downstream to 10.5 upstream. The dimensionless pressure ratios is given by

$$\frac{\tilde{P}_{max}}{P_L} = \frac{\tilde{p}_{max} Ca}{p_L}$$

where

$$Ca = \frac{\mu U_{scale}}{\sigma} = \left( \frac{\mu^2}{\rho \sigma D} \right) Re = Oh^2 Re$$

is the capillary number, $P_L = \Delta P_{interface} = 2M\sigma$ is the pressure jump across the liquid-gas interface and $p_L = P_L/(\sigma/R_c)$ is the capillary pressure made dimensionless by the Laplace pressure of a cylinder of radius $R_c$, and $Oh$ is the Ohnesorge number. $M$ is the mean curvature of the interface. For a 6-mm channel of water the Ohnesorge number is $Oh = 0.0015$. For flow at a Reynolds number of 1159, the Capillary number computes to 0.0027. The maximum value of $\tilde{p}$ along the surface in the smooth boundary case is 73 for a capillary (Laplace) pressure of 1.1 (from the finite element computation contour plot). The pressure ratio is then

$$\frac{\tilde{P}}{P_L} = \frac{73}{1.1} \frac{0.0027}{0.217} = 0.217$$

Thus the biggest dynamic pressure effect along the free surface is about 21.7% of the capillary pressure in this case and would be expected to influence the meniscus shape significantly.

IV. CONCLUSIONS

The major factors that influence the magnitude of the boundary slip are the pitch and slip fraction, boundary roughness and Reynolds number. The slip fraction increases as pitch
and contact angle increase and as wire radius decreases. Slip length was found to increase monotonously with increase in pitch and contact angle, and decrease with increase in wire radius. Significant effective slip was calculated numerically even though it is lower than the prediction of the Lauga and Stone model (a periodic slip, no-slip cylinder). This is due to the added roughness in our open capillary channel model from both the wire and interface curvatures and protrusion into the flow. The slip fraction functionality of slip length for Stokes flow was in excellent qualitative agreement with, and about 2% lower than, the logarithmic scaling of Lauga and Stone. This indicates that even in the most non-wetting case and the largest pitch studied, drag attributable to this wire curvature still persists. The flow boundary roughness is determined by the wire and the pressure at the liquid-air interface. As the wire protrudes more into the flow, the boundary roughness increases constricting the flow, distorting the streamlines and causing recirculation behind the wires and thus resulting in degraded slip. For a cylindrical interface, as the contact angle is decreased, roughness due to wire penetration into the fluid increases, and the slip decreases as a consequence. This is due to both the constriction of the flow and fluid recirculation behind the wires. As the interface pressure is decreased or increased, the boundary becomes rough through either the interface becoming sucked in or bulged out respectively. For a bulged-out interface, the effective slip is influenced by an increase in flow cross-section and also an increased influence on the core of the flow by an increase in solid contact area. The trade-off between these two competing influences determines the effective slip. For a sucked-in interface, the flow is more shielded from the core of the flow due to a decrease in solid contact area but also on the other hand the flow cross-section is reduced. A trade off between these two influences will determine the effective boundary slip. Because of the interplay of
these two competing phenomena, an interface pressure that gives maximum or optimum slip can be inferred. Generally speaking, for a given pitch and wire radius, the most non-wetting wire with a cylindrical interface will give maximum slip. In this geometry, inertial effects will always be present because of the alternating slip and no-slip boundary. This becomes more important beyond the Stokes flow regime and slip is observed to start dropping above a Reynolds number of 50.

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**Appendix A: Meniscus shapes**

1. **Contact angle specification**

   The characterization of interface shape is done by dimensionless parameterization. If the contact angle is specified, then parameterization can be done with respect to the position of the contact fluid contact line with the wire, $s_m$:

   $$ s_m = \theta_c - \pi + s_w $$  \hspace{1cm} (A1)

   The intersection of the meniscus with the wire is characterized by the radius of the meniscus itself $r_m$ and the center of this radius $r_{mc}$:

   $$ 1 - r_w \cos s_w = r_{mc} + r_m \cos s_m $$  \hspace{1cm} (A2)
\[ r_w \sin s_w = L/2 - r_m \sin s_m \]  

(A3)

Eq. A3 is solved for the radius of curvature of the meniscus:

\[ r_m = \frac{L/2 - r_w \sin s_w}{\sin s_m} \]  

(A4)

The position of the center of curvature of the meniscus can then be found from Eq A2:

\[ r_{mc} = 1 - r_w \cos s_w - \left[ \frac{L/2 - r_w \sin s_w}{\sin s_m} \right] \cos s_m \]  

(A5)

The mean meniscus curvature \( M \) at the point \( s_m = 0 \), which specifies the Laplace pressure is given by:

\[ M = \frac{1}{2} \left[ \frac{1}{r_m} + \frac{1}{r_{mc} + r_m} \right] \]  

(A6)

From Eq. A6, if \( M \) is specified, then we can solve for the meniscus center \( r_{mc} \)

\[ (2Mr_m - 1)r_{mc} = 2r_m - 2Mr_m^2 \]  

(A7)

and,

\[ r_{mc} = \frac{2r_m(1 - Mr_m)}{2Mr_m - 1} \]  

(A8)
REFERENCES


CHAPTER SIX

Hydrostatic stability in springs with highly water-repellent walls in normal gravity

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Static stability and compliance in minimally supported helical channels in normal gravity is important for potential applications. The Bond number which quantifies the relative importance of gravitational and capillary effects is a significant governing parameter for the stability of channels formed by wires bridged by liquid. This parameter is dependent on the size of the system, the prevailing gravity, the support structure fraction (determined in this case by the wire diameter and pitch) and some physical properties of the liquid. The substrate wetting also plays a role because highly water-repellent walls tend to constrain the meniscus inside the channel more than wetting walls. In this work, stainless steel single helix springs with wetting and non-wetting walls were studied at different Bond numbers. The static stability and compliance trends are herein reported. It was determined that stability decreased and compliance increased with Bond number and substrate wetting. Quantitative agreement between the data and zero Bond number theory was demonstrated at low Bond number. The data for the superhydrophobic springs also showed high non-wetting with contact angles exceeding 150° and contact angle hysteresis of up to 30°. A quantitative agreement between data and theory became less demonstrable as the Bond number increased, due to amplified gravitational effects.

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I. INTRODUCTION

Fluid interfaces under the main influence of surface tension or capillarity have been studied for many years. The Young-Laplace equation gives a robust physico-mathematical description of the phenomenon:

$$\Delta P = \sigma k = \sigma \left(1/R_1 + 1/R_2\right)$$  \hspace{1cm} (1)

Where $\Delta P$ is the pressure difference across a two-fluid interface when the mean interface curvature is $k/2$, the principal radii of curvature of the interface are $R_1$ and $R_2$ and the interfacial tension is $\sigma$. The more highly curved an interface is the higher the pressure difference across it and thus the greater the tendency to instability. When the bifluidic interface is supported by a solid, the unconstrained 3-phase contact line moves until an equilibrium contactangle $\theta_c$ between this bifluidic interface and the solid-fluid interface is established:

$$\sigma_{SV} - \sigma_{SL} = \sigma_{LV} \cos \theta_c$$  \hspace{1cm} (2)

The different interfacial tensions are identified by subscripts in Eq. 2 where S refers to solid, L to liquid and V to vapor. Two distinct possibilities for the interface dynamics may be identified. The first is a situation where the 3-phase contact line is constrained by pinning on a sharp edge (here contact angle need not be macroscopically satisfied) and the second is that the contact line is allowed to move while maintaining a constant contact angle. Static stability of capillary interfaces is most relevant when surface tension effects far outweigh inertial, gravitational and viscous effects i.e where the Weber $We$, Bond number $Bo$ and Capillary $Ca$ numbers are, respectively, much less than unity. For a fluid with density $\rho$,
surface tension $\sigma$ and viscosity $\mu$, flowing with a velocity $v$ in a channel of inner radius $R$:

\[
We = \frac{\rho v^2 R}{\sigma}
\]

(3)

\[
Bo = \frac{\rho g D}{(\sigma/L/2)} = \frac{\rho g RL'R_c}{\sigma}
\]

(4)

\[
Ca = \frac{\mu v}{\sigma}
\]

(5)

where $R_c$ is the coil radius in our spring geometry, $L$ is the dimensional pitch and $L'$ is the pitch non-dimensionalized with respect to $R_c$.

Probing stability in open capillary channels is important because of the various existing and potential technological applications of open channel capillary flow in both terrestrial and extraterrestrial environments. It is believed that static pressure stability limits will determine the pressure gradient available for flow. Due to practical (stability) limitations, open channel capillary flow is restricted to situations where the surface tension forces outweigh gravitational forces, i.e. where the Bond number $Bo = \Delta \rho g R^2/\sigma << 1$. Low $Bo$ can be achieved in microgravity ($g \to 0$), and in normal gravity in two-fluid isodensity systems ($\Delta \rho \to 0$) or for very small hydraulic cross-sections in normal gravity ($R \to 0$). These flow applications include terrestrial microfluidics and intensified processing (microscale open stable channels are arrayed to achieve desired throughput i.e “numbering up” rather than scaling up\(^1\)), cleaning particulates or other impurity from an air flow, arterial wicks in heat pipes, cryogenic fluid management in space to guarantee fluid outflow, temperature control systems and materials processing. Due to these potential applications, stability and capillary-driven flows in various support geometries have been probed. These geometries include sharp edged grooves, flat surfaces with wetting strips and helices. Lowry and Thiessen\(^2\) analytically probed interfacial stability on infinitesimal wire supports for a contact line pinned on the wire and also on polygonal arrays of straight wires (a special case of multiple helices of infinite pitch) at
$Bo = 0$. They considered that the stability was a function of the volume per unit length, helix pitch and number of wires. Bernate and Thiessen\(^3\) developed a theory for predicting the stability of monohelically supported bifluidic interfaces at $Bo = 0$. The stability in this case is a function of volume per unit length, pitch, contact angle, and the normalized wire radius. Their experiments in an isodensity ($\Delta\rho \rightarrow 0$) system with wetting water contact angle ($<90^\circ$) and a normalized wire radius (with respect to the helical coil radius) of about 0.1 yielded excellent agreement with theory. Oelerich\(^4\) probed the stability of a wetting microspring at low $Bo$ ($R_{eff} \rightarrow 0$) and a wire radius of about 0.1, and found that local stability data agreed with the theory of Bernate and Thiessen for pinned contact line at lower pressures and fixed contact angle at higher pressures. Calculations in the parameter space of pressure, pitch, wire radius and contact angle showed that other parameters being constant, the interface would be more stable as contact angle is increased\(^3\). This work therefore seeks to experimentally investigate the interface stability for highly water-repellent wires ($\theta_c > 150^\circ$) and dimensionless wire radii (normalized by the coil radius) in the vicinity of 0.1 for single helix microsprings and other single helix springs up to 20 times larger in normal gravity at different pitches (different Bond numbers).

II. METHODS

A. Spring preparation and set up

Spring hydrostatics is very important because it provides a convenient method of characterizing the substrate in terms of the stability, compliance, contact line dynamics, contact angle and contact angle hysteresis. Information is thus obtained about the channel compliance and static pressure limits and therefore the maximum pressure driving force for flow\(^4\).
Lowry and Thiessen\textsuperscript{2} had previously developed a theory for the static stability of free surfaces pinned on helical wire supports. Bernate and Thiessen \textsuperscript{3} modified and developed this theory for stability of the single helix case. This theory is very useful for predicting the extremes for the channel pressure stability limits in low Bond number situations. To enable compliance and static stability measurements in the hydrophobic springs, a static test system, schematically depicted in Fig. 1, was designed and constructed.

![Hydrostatic experiment schematics](image)

**FIG. 1.** Hydrostatic experiment schematics (a) shows the imaging system for the spring and (b) is a close up showing how the spring is assembled in the custom compression fitting for one end of the spring. The fitting on the other end is a mirror image of the one shown in (b).

Two sizes of commercially available carbon stainless steel extension springs (Associated...
Spring Raymonds were used in this experiment. The first was a 1/8-inch spring with 0.125 inch outside diameter and 0.013 inch wire diameter. The second was a 1/4-inch spring with 0.250 inch outside diameter and 0.017 wire diameter. The wire diameters were chosen to be small for minimizing solid contact with liquid in the spring for a given pitch while being large enough to give the needed mechanical integrity under terrestrial gravity conditions. The outside diameters were chosen with standard fractional inch dimensions to be compatible with commercially available ferrules for attachment to custom chucks or injectors. The spring together with custom aluminum compression nuts and commercial ferrules are threaded into custom chucks at the two ends of a custom lathe with synchronized shafts. This allowed the spring to be spun around its axis at around 120 rpm without twisting for the hydrophobic spray/spin coating process. One end of the lathe could be moved axially to stretch the spring and give a large pitch during coating to allow better access for the spray to coat all surfaces of the wire. During the spraying process the faces of the compression nuts were also coated. This was important to avoid leakage at the ends of the spring. A superhydrophobic coating was applied to the spring as it was being spun in the lathe at 120 rpm using an air brush that is being manually moved back and forth about 8 times along the length of the spring. The superhydrophobic ORMOSIL sol-gel was prepared according to a modification of
Budunoglu and co-worker’s recipe\textsuperscript{5}, diluted with excess methanol (14 mL per 10mL sample) to inhibit post-sonication re-gelling of the gel, and sonicated in a Cole-Parmer Ultrasonic Processor CP750 at 450 W for 3 minutes to ensure fine colloidal suspension of the particles before loading the solution into the air brush. Prior to coating the stainless steel springs (Associated Spring Raymond), glass slides cleaned in methanol in an ultrasound bath were coated as a simple preliminary test of the efficacy of our prepared hydrophobic sol-gel. The slides were coated with a fine mist of the suspension using an airbrush with a pneumatic pressure of 35 psi about 2 inches away from the surface with about 8 times back and forth movements. The slides were then allowed to cure for at least 8 hours to achieve the spring-back effect\textsuperscript{5}. This effect occurs when the capillary forces at the liquid-gas interface are too small to cause pore collapse during normal atmospheric drying, mainly due to thin film coating, thus leading to an air-filled very porous superhydrophobic structure on the coated substrate. Droplets of water were then placed on the coated slides and observed to bead up and roll off at very small angles to the horizontal table surface. This indicated that the prepared sol-gel was indeed water-repellent with a high contact angle. The stainless steel spring channel was then similarly cleaned, assembled on the lathe as described above and spray/spin-coated at 120 rpm under identical conditions as the slides. After spraying, the relatively thin film was allowed to cure overnight to achieve the spring-back effect\textsuperscript{5} and form a highly porous superhydrophobic aerogel coat. The spring was then dismantled and threaded into two identical custom aluminum injectors one of which is shown in Fig. 1(b). The spring is firmly held in place using commercial plastic ferrules (Upchurch) whose ends grip the end of the custom compression nut tightly. This compression nut-ferrule-spring assembly is then tightly screwed into the threaded flow-development section as shown. This assembly was then
mounted on a horizontal platform using two vertical posts and a slider on each end. The sliders allow the spring to be stretched to the desired pitch. The fluidic lines in the system (0.125-in. OD clear teflon tubes from UpChurch Scientific$^R$) were bled thoroughly with distilled water (used for all the experiments) and the channel connected to a water reservoir situated on a vertically adjustable stage and to a diaphragm differential pressure transducer (Validyne$^R$). The transducer with an output range of $\pm 10$ V is connected to a Validyne carrier demodulator which routs the analog signal through a Measurement Computing$^R$ 1408-FS data acquisition board to a computer with a LabVIEW$^R$ pressure acquisition program. One end of the differential transducer is open to the atmosphere so that the output is a gauge pressure. Data can be acquired at rates up to 10000 Hz. An independent calibration relates static pressure to transducer output by adjusting the reservoir in equal increments and acquiring voltage data. The transducer contains a sensitive diaphragm which deflects according to the pressure exerted on it through the fluidic lines plumbed to it. The reservoir, plumbed to the transducer, is raised by 0.1 inch by turning the screw jack of the platform on which the reservoir sits by one clockwise rotation. This system is accurate within a one-hundredth of an inch. About 5 minutes is allowed to ensure that the diaphragm has achieved maximum deflection at this level. The voltage data on the computer screen is simultaneously monitored to ensure that it is steady. Voltage data is then recorded for about 5 minutes for subsequent data analysis. The level of the reservoir is changed in this way for equal increments, voltage data acquired and a calibration of voltage versus reservoir level produced.

A specially designed stainless steel cup was then made level to the center of the channel using the imaging system and laser and the cup plumbed to the reservoir for fluidic contact.
The reservoir was then adjusted until the water meniscus was flat and level with the sharp tip of the cup. This indicates that the reservoir and the channel are now at the same level and this setting was then taken as the zero of Laplace pressure or pressure reference and the corresponding voltage recorded.

B. Imaging

The imaging system (Fig. 1(a)) consists of a machine vision camera (Basler Scout scA-130gm), a collimated light source whose wavelength (green) is in the optimal range for the camera’s sensor and an object-space telecentric macro lens (Opto Engineering). The magnification and shape of the image formed by this object-space telecentric lens is insensitive to the object distance or position in the field of view. The lens gives an orthographic projection of the object (i.e. projects a 2D image of the 3D object). The camera is connected to the computer via a Gigabit Ethernet (GigE) cable for high-speed image acquisition. The reservoir was then carefully adjusted by 0.1 inch, with a 5-10-minute wait in between until a stable channel was established (as shown by the invariance of the transducer voltage measurements) after which full-channel image scan was acquired. A full-channel scan was accomplished by first carefully aligning the camera and light source (which translate together as they are placed on an aluminum beam going under and perpendicular to the channel). This camera-light source assembly is attached to a horizontal stage with a double helix screw which is in turn attached to a digital counter. This system translates at a rate of 10,000 counts/inch. The digital counter is used to move the imager for predetermined counts corresponding to one image or chunk of the whole channel. After this setting an image is acquired, the counter zeroed and the imager carefully translated the same number of counts for acqui-
position of a second image. It is important to translate carefully so as to prevent image overlaps or skips. This is repeated until the whole channel is imaged. The reservoir was then raised to increase the static pressure by the desired amount and the scanning procedure repeated. The pressure was raised in equal increments and scans acquired until the channel blew out. For channels that can hold pressures below the reference, pressure adjustments were made by lowering the reservoir below the reference point by the same increment for which they were raised and scans acquired until the channel breaks. A camera calibration was made by imaging a standard calibration slide with markings 0.5 mm apart. This calibration was used in conjunction with the NIH freeware program ImageJ to measure dimensions of the spring from the images acquired.

C. Data smoothing procedure

The diameter profile is determined using a MATLAB code for finding the top and bottom edge of the channel for every column of pixels in the image as illustrated in Fig. 3,

\[ D(z_i) = y_b(i) - y_t(i) \quad i = 1, \ldots, N_c \]

where \( N_c \) is the number of columns in the image and \( z_i \) is the horizontal coordinate of column \( i \) that is determined from the magnification calibration. To determine the compliance profile it is helpful to smooth the raw diameter profile using a spatial discrete Fast Fourier Transform (FFT) smoothing process to eliminate frequency components related to the periodicity of the coil itself. The raw diameter profile is first detrended by subtracting the best-fit line to the \( D(i) \) data

\[ \tilde{D}(z_i) = D(z_i) - D - m(z_i - z_0) \quad i = 1, \ldots, N_c \]
where \( m \) is the slope of the best-fit line to the \( D(i) \) data and \( z_0 \) is the horizontal mid point of the image. The detrended diameter profile is Fourier transformed to give Fourier coefficients \( c_i \) and a smoothed diameter profile is then constructed by truncating the Fourier series using Lanczos smoothing\(^6\) to reduce the Gibb’s phenomenon.

\[
D_s(z) = \bar{D} + m(z - z_0) + \text{Re}\{c_1\} \\
+ \sum_{k=2}^{N} \sin(\pi(k - 1)/N)\text{Re}\{c_k e^{i2\pi(k-1)(j-1)/N}\}
\]

(6)
III. RESULTS & DISCUSSION

The local channel diameter and compliance will depend on the local wetting condition and the local pitch. Also, channel sag for such a minimally supported channel will affect local diameter and compliance because of gravity (the diameter and compliance increases in the direction of the sag). The springs used in this work were found to be of relatively uniform pitch across. However, the coating technique, albeit carefully done, and the poor substrate-coating adhesivity produced some energetic non-uniformities. This makes it imperative to fully characterize the springs by scanning the entire spring at the different static pressures. This is necessary both for comparison with theory and for measurement of pressure profile along the springs during stationary flow using imaging. Fig. 4 shows a 1/4 inch OD channel

![Channel Images](image)

**FIG. 4.** Pictures showing (a) lowest pressure (0.1in. H$_2$O) and (b) highest pressure (0.9 in. H$_2$O) in a 1/4-inch spring with a pitch $L'$=0.3. Note the conspicuous meniscus bulge between the wires at the highest static pressure.

at the two extremes of static pressure measurement. Note the visibly bulged out meniscus in the highest pressure case.
A. Coating robustness

It was important to probe the robustness of the coating because of adhesivity issues noticed with the aerogel coating. The aerogel was seen to flake off the stainless steel substrate if the spring is accidentally vibrated. This led to concerns about its robustness over time during use. Consequently, the diameter profile was monitored over a span of several days. Fig. 5 shows the diameter profiles for the channel for different hydrostatic pressures. These show that for the first two days the channel held slightly above 0.9 inches of water (the experiment was performed with increments of 0.1 in. H₂O and the channel blew out at 1.0 in. H₂O). The increments in diameter (spacing of the curves) with pressure are observed to be fairly uniform which indicates uniformity in compliance even though there are obvious non-uniformities in wetting (as shown by the waviness in the smoothed diameter profiles). Regions of larger diameters correspond to the more wetting portions of the channel. These more wetting portions are thought to be due to the coating flaking off because of local adhesivity issues. In contrast to Oelerich’s results where he observed alternating regions of curve contraction (closer) and dilation (more spaced) which he attributed to pitch non-uniformity, we note in our case that the curves appear evenly spaced suggesting a good uniformity in pitch. We see a diameter variation (due to wetting variation) without compliance variation which suggests that perhaps a variation in wetting affects diameter without much effect on compliance. This is observed in Fig. 6 where the compliance does not change much as the channel gets more wetting (Fig. 5) over the course of two weeks. As a further characterization of our channel, local compliance plots were made for each hydrostatic experiment. This would serve as a good measure of the contact line dynamics, the uniformity, the hysteresis behavior, the overall stability and the suitability of the imaging technique for measuring the
pressure gradient along the channel. The minimum sustainable pressure changed from 0.1 to 0 in. H$_2$O from day 1 to day 2 and from 0 to -0.4 in. H$_2$O from day 2 to day 14. This is attributable to the spring getting more wetting due to some local coating failure along the channel. Also, it is seen that the diameter at the ends on day 14 are larger which indicates

FIG. 5. Diameter profiles along the axis taken on the same 1/4-inch channel over the course of several days, \( L_c = 14 \) in., and dimensionless pitch \( L' = 0.3 \). The legend on the right of each figure shows the static pressures in inches of water. (a) 02/19/13 and (b) 02/20/13 (c) 03/02/13 and (d) 03/06/13. Note that stable pressure ranges for all the measurements were reproducible to extents that did not vary much.
FIG. 6. Compliance measurements over several days for the same 1/4in. channel shown in Fig. 5

For a given day, the data shows minimal scatter in compliance indicating good uniformity in wetting and geometric properties. The difference in compliance from day to day is attributable to the lack of robustness of the coating.

highly wetting behavior at the ends. Because there was no readily observable coating abrasion at the extremities, we speculate that there may be some sort of electronic interaction at the junction between the dissimilar aluminum holder and the stainless steel spring which increases the surface energy and makes the substrate more wetting. However interesting, we concede that this a material science problem. We also notice from the diameter profiles that the compliance for the most wetting case on day 14 was the least because of the negative pressures it holds. Fig 6 shows the average axial compliance on the different days. It is observed that there is minimal scatter in the axial compliance for any given day which
attests to the good uniformity of the channel wetting and pitch. This further suggests that for the same pressure driving force and the same flow rate, we would expect that the surface roughness would be similar. An increased pitch is expected to lead to higher compliance since the meniscus motion is less constrained. Fig. 7 shows the diameter profile for a 1/4-inch hydrophobized spring with a higher pitch of 0.52. Diameter profiles for two flow rates are shown superimposed on the static measurements. It is seen that the diameter profiles for flow dip in the direction of flow indicating that as pressure drops in the flow direction, the diameter also drops. The diameter profile for the 300 mL/min flow (dotted lines) is steeper than that for the 100 mL/min (darker full line) showing that this measurement technique is sensitive enough to discriminate between flow diameter profiles. This indicates that the hydrostatic calibration may be used to measure the flow pressure profile along the channel to study flow development effects in small aspect ratio channels. As evident from Fig. 7,

![Smoothed diameter profile for L_c=11.23 in., L'=0.52 data of 03/26/13](image)

**FIG. 7.** Axial diameter profiles measured on another 1/4 in. hydrophobized channel with greater pitch (L_c=11.23 in., pitch L'=0.52). Note the dip in diameter for the lowest profile. This is due to low pressure and high water repellence.

the higher pitch results in an abbreviated stable pressure range as predicted theoretically.
The large dip in diameter at the injection end for the first “stable” pressure of 0.2 in. H\textsubscript{2}O is due to a partial detachment of the meniscus from the wire at the top of the channel due to a combination of the superhydrophobicity (highly non-wetting), gravity and the slight tilt due to channel sag. Also noticeable from the diameter profiles is the larger change in diameter with pressure. This expected higher compliance can also be attributable to the higher pitch and the consequently more pronounced meniscus movement because there is less solid confining the meniscus.

B. Theoretical comparisons with compliance data

It is important to compare static compliance data to theory in order to elucidate the wetting properties and contact line dynamics. The higher diameter segments usually correspond to the more wetting and also the sagging segments (towards the middle) and may change contact line dynamics as pressure goes up. The Bernatez-Thiessen theory for the stability of helically-supported interfaces is used to predict the dynamics of such surfaces at zero Bond numbers\textsuperscript{3} and low Bond numbers.\textsuperscript{4}

Fig. 8 is a schematic depicting a pinned contact line position $\phi_L$ and a fixed contact angle $\theta_c$. These are the parameters used in the Bernatez-Thiessen theory in conjunction with the dimensionless wire radius and pitch to predict the dynamics for a given pressure range. It is not unreasonable to assume that the more wetting portions may mutate from a pinned contact line at lower pressures to moving contact line at higher pressures\textsuperscript{4} depending on how wetting they are while the portions exhibiting high hydrophobicity may retain fixed contact angle behavior because of the associated water repellent nature. However, the aforementioned mutation may not be readily apparent because of the small pressure range (less than
FIG. 8. Schematics depicting how the fixed contact angle and the pinned contact line position are specified in the Bernate-Thiessen theory.

1 in. H$_2$O) that the channel can hold. The contact dynamics can be described by comparing the data to theory developed for such helical support structures by Bernate and Thiessen$^3$. Calculations are made using dimensionless channel geometric parameters, the dimensionless pressure range and wetting parameter (fixed contact angle or fixed contact line). These calculations are then compared to the experimental data and the best fit determined. The best fit curve or curves may then be used to proffer the best qualitative description of the physical phenomenon$^4$, and also a quantitative estimate of the contact angle and contact angle hysteresis. Fig. 9 shows dimensionless diameter vs. dimensionless Laplace pressure data and theory for the 1/4-inch springs monitored over a period of 2 weeks with the same Bond
number of 0.32. The data (squares) show that the contact angle decreases from day 1 (Fig. 9 (a)) to 2 (Fig. 9 (b)) with day 1 showing contact angle hysteresis of about 20° (receding angle of 140° and advancing angle of 160°). The receding contact angle corresponds to where the data agrees closely with theory at lower pressures and the advancing contact angle to where the data agrees with theory at higher pressures. There appears to be identical contact angle for day 2 and day 10 (Fig. 9 (c)) indicating very little change in the substrate energy for these two days. However we notice from the data of day 14 (Fig. 9 (d)) that there is an abrupt increase in substrate energy as it gets more wetting and the data follows a pinned contact line (at 110° measured from directly away from the center of the coil) even at the highest experimental static pressure. It is expected that the meniscus will be pinned to the wire when it is more wetting than when it is more water-repellent. This more so because the channel now holds negative pressures (Fig. 5 (d) and Fig. 9 (d))

Fig. 10 shows diameter profiles for two different 1/8-inch springs at different pitches and Bond numbers. The diameter profiles for the higher pitches (Fig. 10 (b) and (d)) show slight but noticeable changes in compliance for some segments as the pressure goes from low, through intermediate to high. Fig. 11 (a)) shows a comparison of the normalized diameter vs. pressure curve data (asterisks) for the smaller pitch with theoretical calculations for different contact angles $\theta_c$ and one fixed contact line position $\phi_L$.

It is observed that the data lie between theoretical curves for $\theta_c = 150^\circ$ to $170^\circ$ which gives us more confidence that the channel is superhydrophobic ($\theta_c > 150^\circ$). The increase in local contact angle as the pressure is increased (increased advancing contact angle) shows static contact angle hysteresis\textsuperscript{7}. Hysteresis of up to 40° has been reported even for superhydrophobic substrates. This hysteresis is attributable to substrate chemical heterogeneity,
FIG. 9. Local compliance data compared to theory\(^3\) for the same channel over the course of several days\((L_c=14\text{ in.},\ \text{pitch } L'=0.3,\ \text{Bo}=0.32\) (a) 02/19/13 (b) 02/20/13 (c) 03/02/13 and (d) 03/06/13.

substrate roughness, surface deformation, or liquid adsorption/desorption\(^7\), that may produce local energy barriers \(^8\) that promote contact line motion (thus de-pinning the contact line). Fig. 12 (a) shows a similar trend for the low pitch case with most of the data (squares) lying between 150° and 178°. In some industrially relevant processes like dip coating, contact angle hysteresis is important\(^7\), while in the case of slip flow it would be detrimental. Con-
FIG. 10. Diameter profiles along the axis taken on two different 1/8-inch channels with different pitches. The legend on the right of each figure shows the static pressures in inches of water. (a) \( L' = 0.39, \ Bo = 0.099 \) (b) \( L' = 0.718, \ Bo = 0.18 \) (c) \( L' = 0.374, \ Bo = 0.093 \) (d) \( L' = 0.55, \ Bo = 0.14 \). The profiles for (a) and (b) are from the same spring while that for (c) and (d) are from a different spring.

tact angle hysteresis is detrimental to slip because of the stick-slip dynamics on a substrate with contact angle hysteresis. The fluid will stick to the substrate on the receding end and undergo more slip on the advancing end. This would act to reduce the slip length. Better coating using adhesion promoters is expected to reduce this hysteresis. An increase in pitch
FIG. 11. Local compliance at a highly non-wetting column of a 1/8-inch spring compared to theoretical predictions. (a) The measured dimensionless pitch $L'=0.374$ and measured wire diameter $R_w=0.1185$, $Bo=0.093$ (b) $L'=0.55$, $R_w=0.15$, $Bo=0.140$

FIG. 12. Local compliance at highly non-wetting column of a 1/8-inch spring compared to theoretical predictions. (a) The measured dimensionless pitch $L'=0.390$ and measured wire diameter $R_w=0.124$, $Bo=0.099$ (b) $L'=0.718$, $R_w=0.15$, $Bo=0.180$

is expected to affect the compliance and contact line dynamics of this channel because an increase in pitch would lead to more meniscus movement for the same hydrostatic pressure
change which could lead to higher compliance and modified contact dynamics. Also the relative importance of the gravitational effects as quantified by the Bond number will increase with pitch (Eqn. 5) and thus the quantitative deviation of the data from the theory will increase. This deviation is shown in Fig. 11 (b) and Fig. 12 (b). The quantitative deviation makes it difficult to quantify the contact angle and contact angle hysteresis in this case.

IV. CONCLUSION

Stability and static compliance measurements were done on different channels with different Bond numbers less than unity. It was found that the stability decreased and the compliance increased with Bond number due to elevated gravitational effects compared to capillary effects. This is attributable to the reduced confinement of the meniscus due to reduced support structure as the pitch is increased for a given wire diameter. A comparison of the normalized diameter versus pressure profile data with theory shows good agreement at lower pitch (lower Bond number) and less agreement at higher pitch. The higher pitch disagreement, with the data about 2% higher than theoretical predictions, is attributable to elevated gravitational influence due to less meniscus confinement. Also the lower pitch data for the non-wetting channels (superhydrophobic, $\theta_c \geq 150^\circ$) showed a $20^\circ$ contact angle hysteresis with the advancing contact angle greater than the receding (data at higher pressure tending towards higher contact angle). This hysteresis is expected to reduce slip by inducing stick-slip on the surface. It can be reduced by making the coating of the surface more homogenous by, for example, using adhesion promoters. The measured hysteresis is in the range reported for heterogenous non-wetting surfaces in extant literature.
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REFERENCES


CHAPTER SEVEN

Drag reduction for flow in superhydrophobic springs

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The steady flow of water was studied in stretched extension springs that are treated with a superhydrophobic coating. Large-bore capillary channels formed from springs are envisioned for phase separation and liquid-gas contacting applications in the microgravity environment and for various small-scale terrestrial capillary transport applications. It is believed that terrestrial stability and flow limits will suggest the lower bounds in space applications.

Water was flowed in channels with length-to-diameter ratios ranging between 32 and 200 at flow rates up to 628 mL/min. The pressure profiles in the channels during flow experiments were measured by imaging to measure the diameter profile which is related to pressure through hydrostatic calibration. A straight line was fitted to the flow pressure profile and the pressure drop calculated from this fit. An independent measure of pressure drop was obtained from a differential pressure transducer. The slip length for a smooth tube of the same inside diameter as the spring that achieves the same pressure drop when entrance conditions and length-to-diameter ratio are the same is taken as a measure of the effective slip of the channel wall. Slip lengths in the vicinity of 26 µm were measured for the 1/4-inch spring and slip lengths between 70 and 140 µm for the 1/8-inch spring. These are in the high end of measured slip lengths reported in extant literature.

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I. INTRODUCTION

The development of techniques which produce significant drag reduction in flows are having profound effects on existing and emerging technologies. The benefits of drag reduction include pressure drop reduction in micro and larger scale fluidics and the attendant reduction in pumping power requirements, speed and fuel efficiency of marine vessels, increase in settling speeds of immersed solids, etc.

Drag reduction in conduits has been produced in the past by active means which include transverse wall oscillation and transverse traveling wave excitation to modify wall shear stress in turbulent flows\cite{1,2}, blowing and suction in opposition to the wall normal fluid velocity in turbulent flows\cite{3}, using deformable dimples at the channel bottom in compressible turbulent flow\cite{4}, and creation of bubbles at the conduit wall. However, with advances in coating chemistry and technology, passive drag reduction surfaces which entail less energy expenditure and cost for maintaining drag reduction are being developed. Such surfaces typically exhibit macroscopic hydrophobicity with a contact angle above 120° and superhydrophobicity with a contact angle above 150°. The so-called superhydrophobic surfaces are commonly formed by a combination of chemical hydrophobicity and surface asperities\cite{5-8}, originally inspired by the lotus leaf (biomimetics)\cite{9}. However, investigation had surprisingly shown that the lotus leaf which was originally believed to have a hydrophobic wax surface, actually had a hydrophilic wax surface ($\theta_c = 74^\circ$)\cite{10} and that only the micro and nano surface structures were responsible for its superhydrophobicity, suggesting that an intrinsically hydrophilic surface can be made superhydrophobic or at least hydrophobic by careful engineering of surface asperities (hierarchical structuring) without any hydrophobic chemical treatment. This suggests that even though hydrophobicity contributes to drag reduction, it is not a suffi-
cient condition. There must also be a wall structure that consists of air-trapping asperities that lead to essentially shear-free portions along the wall. Generally speaking, these surface asperities could be a combination of small-scale substrate roughness, additional roughness attributable to the coating substance, and also larger-scale wall structures attributable to channel geometric engineering (e.g. surface grooves, holes, and posts). The size of these wall structures relative to the hydraulic diameter of the flow is of critical importance. A combination of these asperities usually with the chemical non-wetting gives rise to higher contact angles coupled with higher shear-free regions and can, potentially, lead to a maximization of drag reduction. The Cassie-Baxter equation relates the amount of substrate roughness to the contact angle for a composite surface consisting of solid-liquid and air-liquid portions and predicts that contact angle increases with surface roughness and liquid-air fraction

\[ \cos \theta = R_f f_{SL} \cos \theta_0 - 1 + f_{SL} \]  

or

\[ \cos \theta = R_f \cos \theta_0 - f_{LA}(R_f \cos \theta_0 + 1), \]  

where \( \theta \) is the contact angle on the composite, \( \theta_0 \) is the contact angle for the solid-liquid interface, \( f_{SL} \) and \( f_{LA} \) are respectively solid-liquid and liquid-air fractions and sum up to unity; \( R_f \) is the roughness factor for solid in contact with liquid. The higher contact angle of the roughened substrate is due to the chemical hydrophobicity preventing (at low to moderate hydrostatic pressures) the water from penetrating the air pockets trapped between adjacent peaks of the asperities and making the transition from highly non-wetting to wetting, the so-called Cassie-Wenzel transition. The advantage of air-trapping wall structure is complicated by interface deformation into the air cavity at elevated pressures because of the attendant flow field distortion and form drag. Therefore, it is also important to con-
control the channel pressure to achieve as smooth a surface as possible. Also of importance is the orientation of the flow with respect to the wall structures. Flows oriented in the same direction as the wall structures are expected to give higher slips than flows transverse to the wall structures because of less flow field distortion in the former. Synthetic coatings via sol-gel chemistry have been formulated which when properly applied to a substrate can yield substrate-specific contact angles close to $180^\circ$ (perfect non-wetting)\textsuperscript{6,13–15} with very small water roll-off angles, an important factor for enhancing slip.

Numerous analytical and semi-analytical\textsuperscript{12,16–20}, numerical\textsuperscript{21–23} and experimental\textsuperscript{24–28} studies have been done to quantify the degree of drag reduction, usually through the so-called slip length, for various geometrical configurations of hydrophobic and superhydrophobic surfaces and over the laminar and turbulent flow regimes. Perhaps the most common model for partial slip at a solid boundary suggests that the slip velocity $V_s$ at the wall is proportional to the shear rate,

$$V_s = \lambda \frac{\partial V_z}{\partial r}$$  \hspace{1cm} (3)

The proportionality constant $\lambda$ is termed the slip length and has the geometric interpretation illustrated in Fig. 1, where $z$ is the axial flow direction perpendicular to $r$. The slip length is the distance into the solid at which the velocity profile would linearly extrapolate to zero. A flow conduit with wall slip effectively behaves like an equivalent conduit with its hydraulic diameter augmented by the slip length, thus leading to lower flow resistance.

Theoretical predictions of slip lengths for simple geometries with composite walls (mixed no-slip and perfect or reduced slip boundaries or more succinctly effective slip boundaries) were first investigated by Philips\textsuperscript{18,19} and more recently by Lauga and Stone \textsuperscript{16}. Lauga and
Stone showed that for Stokes flow in a smooth circular cylinder, the slip length normalized with respect to the channel hydraulic radius increases with fraction of shear-free wall and that in the limit of small slip fraction, the effective slip length was higher when the alternating slip-no-slip boundaries were arranged longitudinally to the flow than when they were arranged transversely. This is reasonable because we expect less deformation of streamlines in the former case as the slip portions are aligned with the flow. Also, in the limit of small separations between slip regions (small pitch), they predicted a longitudinal slip length that was twice the transverse. Another interesting analysis is that of Davis and Lauga\textsuperscript{12} where they found that an increase in friction for flow over a bubble mattress may result if the shear-free bubble surfaces are sufficiently curved into the liquid, possibly due to elevated form drag and a constriction of the flow passage. This suggests that even with a larger shear-free surface, a significant curvature of the liquid-air interface can still be detrimental to drag reduction. A more recent and more realistic analysis is the numerical analysis of Samaha and co-workers\textsuperscript{29}. This analysis is more realistic because it was done on randomly

FIG. 1. Geometrical interpretation of the slip-length parameter $\lambda$. 

Liquid

(Shear stress)$_{zr}$=$\mu dV_z/dr$

Solid

$r$

$z$

$V_z(r)$

$V_z(r) = \mu dV_z/dr$
distributed roughness that better mimics natural superhydrophobic surfaces as compared to more expensive and idealized microfabricated ones. They found that slip increased with shear-free fraction and reported a peak dimensionless drag reduction of 30% for random posts relative to staggered ones at gas fractions of 98% but caution that the meniscus stability is strongly dependent on the average spacing (pitch) of the roughness peaks suggesting that for large pitches a catastrophic Cassie-Wenzel transition may result, depending on the prevailing channel hydrostatic pressure. They also reported increase in drag with pressure. Experimental drag reduction studies have been done mainly on fabricated channels of technological interest in different flow regimes and have reported a wide range of slip lengths using direct and indirect measurements (see Table I). Ou and Rothstein made µ-PIV measurements on a silicon wafer microchannel with regularly spaced microridges coated with hydrophobic organosilane and obtained pressure drop reduction of up to 25%. Pressure drop or drag reduction was found to decrease with increasing microchannel depth and decreasing microridge spacing as expected. To lend further credence to these experimental results, a numerical prediction quantitatively fit the velocity data and qualitatively fit the pressure drop reduction data. Lee and Kim rheometrically measured a two-fold increase in slip length over single scale structures using hierarchical structures composed of nanostructures on the sidewalls of microgrates and microposts. The nanostructures essentially trapped more air and increased the shear-free portion. The rather large slip length of 400 µm that they measured for hierarchical grates is believed to potentially influence fluidic drag reduction even at the macroscale. The same authors found that the addition of nanoposts on microposts was beneficial (increased slip by 100%) only when the microposts had a solid fraction above a threshold (10%) and detrimental below this threshold because there was
not enough support to prevent the liquid from penetrating and wetting the nanoposts below this threshold. Thus, the increased pressure for slim microposts leads to meniscus bending and eventual Cassie-Wenzel transition which both degrade slip. Daniello and co-workers report drag reductions approaching 50% using two independent measurements, particle image velocimetry (PIV) and pressure drop. They found appreciable increase in drag reduction with microridge spacing or shear-free size (not merely the shear-free fraction), but not below a critical Reynolds number. Drag reduction was also observed to increase with increase in Reynolds number above this critical value and also increases when both top and bottom walls of the test section were superhydrophobic (for PIV it was necessary to have a hydrophilic (wetting) glass top for optical access). Slip lengths from PIV data were found to be insignificant in the laminar region but greater than 70 µm for a 30 µm wide by 30 µm spaced and greater than 120 µm for 60 µm wide by 60 µm spaced ridges. It was also deduced that for the superhydrophobic surface to impact the turbulent flow, the microridge spacing had to be comparable to the viscous sublayer thickness.

All these observations potentially have influence in designing and manipulating other systems for maximizing drag reduction. The superhydrophobic minimal support capillary channels studied in this work are thought to have certain advantages over microfabricated channels for certain applications. The minimal support of the wire, the superhydrophobic coating and the variable wire pitch (by a simple stretching of the spring) combine to suggest a potentially high drag reduction. However as noted before, roughness due to liquid-gas interface curvature may complicate matters. These types of channels are believed to have potential applications in microgravity phase separation via free surface drop capture, bubble capture by non-wetting channel, microprocessing (process intensification), mass transfer operations (e.g. gas
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$^a$ R is the hydraulic radius of the channel, $\delta$ is the dimensional slip size and L is the pitch, PIV is Particle Image Velocimetry, $\Delta P$ is pressure drop, $V_s$ is wall slip velocity, $\frac{\partial v_x}{\partial y}$ is the shear rate, $\lambda_{eff}$ is the effective slip length.

and particulates scrubbing), as an arterial wick in heat pipes and, heat transfer enhancement from the liquid-gas interface (e.g. chip cooling via engineered microscale wicking systems). Many of these applications may benefit from viscous drag reduction, hence the interest in studying them for that purpose. The overall goal of this study is to push the limits of flow and drag reduction in these channels for pressure-driven flow. The drag will be minimized by
increasing the pitch subject to liquid-gas interface stability limits and controlling the channel pressure to achieve a cylindrical surface (minimizing roughness). If the free surface meniscus for a large pitch can be made cylindrical by adjusting the reservoir pressure, it is expected that significant experimental slip lengths at low flows, comparable to that obtained in other studies can be achieved. Alternatively, inertial effects may be important at higher flow rates and higher reservoir pressures because of roughness related to support wire penetration, alternating boundary conditions and axial curvature of the meniscus between the support coils. A partial slip boundary condition works well for so-called superhydrophobic surfaces when the surface structures that trap gas pockets at the wall are microscopic. The system to be studied here consists of larger free-surface regions between the support structures (coils of the spring) and this can lead to significant form drag and recirculation zones between the coils at higher flow rates. Such recirculation results in extra energy dissipation which may manifest in the form of higher pressure drop. The objective in this work is therefore to maximize drag reduction in helically supported channels with effective slip boundaries. Pressure drop versus flow rate measurements will be taken on 3 and 6 mm diameter channels and compared to pressure drops in fully-developed pipe flow to quantify drag reduction. The channel pitch and flow rate will be increased within the stable range for both channels.

II. METHODOLOGY

A. Channel and equipment preparation

Two sizes of commercially available carbon steel extension springs (Associated Spring Raymond) were used in this experiment. The first was a 1/8-inch spring with 0.125 inch outside diameter and 0.013 inch wire diameter. The second was a 1/4-inch spring with 0.250 inch
outside diameter and 0.017 wire diameter. The wire diameters were chosen to be small for minimizing solid contact with liquid in the spring for a given pitch while being large enough to give the needed mechanical integrity under terrestrial gravity conditions. The outside diameters were chosen with standard fractional inch dimensions to be compatible with commercially available ferrules for attachment to injectors.

FIG. 2. Flow experiment schematics. (a) shows the schematics for the flow and (b) shows the schematics for the architecture of the custom compression nut on the high-level tank or injection end.

The spring was attached to custom-made injectors on both ends using custom-made compres-
FIG. 3. Schematics illustrating setting of the reference pressure or zero Laplace pressure.

FIG. 4. Image acquisition schematics.

sion nuts and commercial plastic ferrules as illustrated in Fig. 2(b). The injectors constituted one-inch outside diameter solid cylinders with a centered axial hole bored to the same diameter as the inside diameter of the spring. One end was machined for spring attachment
as shown in Fig. 2(b) while the other end was machined to accept a commercial compression fitting to attach the tubing from either the source tank or suction tank. The length of the aluminum cylinder was chosen such that the length to diameter ratio of the bored hole allowed for fully-developed flow to be established prior to injection into the spring. The tubing attaching the injectors to the source and suction tanks was of nearly the same inside diameter as the injectors. The spring together with compression nuts and ferrules could be removed from the flow development sections and threaded into custom chucks at the two ends of a custom lathe with synchronized shafts. This allowed the spring to be spun around its axis at around 120 rpm without twisting for the hydrophobic spray coating process. One end of the lathe could be moved axially to stretch the spring and give a large pitch during coating to allow better access for the spray to coat all surfaces of the wire. During the spraying process the faces of the compression nuts were also coated. This was important to avoid leakage at the ends of the spring. A superhydrophobic coating was applied to the spring as it was being turned in the lathe at 120 rpm using an air brush that is being manually moved back and forth about 8 times along the length of the spring. The coating is an ORMOSIL (organically modified silica) aerogel that is prepared by a sol-gel process described by Budunoglu et al.\textsuperscript{6} About 10 mL of the formulated sol-gel was diluted with excess methanol (14 mL) to inhibit post-sonication re-gelling of the gel, and sonicated in a Cole-Parmer Ultrasonic Processors CP750 at 450 W for 3 minutes to ensure fine colloidal suspension of the particles prior to loading the solution into the air brush. The spray coated spring was then allowed to sit for at least 8 hours for the relatively thin coating to cure and allow for the spring-back effect\textsuperscript{6}. The spring-back effect occurs when the capillary forces at the liquid-gas interface are too small to cause pore collapse during normal atmospheric drying, mainly due to a thin film, thus lead-
ing to an air-filled very porous superhydrophobic structure on the coated substrate. Direct reading 150 mm rotameters were available with ranges of 200, 500 and 1200 ml/min. A rotameter was chosen for a given experiment that had a range closely matching the achievable flow rate for a given channel. All rotameters were calibrated by gravity flow and gravimetry before deployment. Flow rates of up to 630 mL/min and 93 mL/min were achieved in the 1/4-inch and 1/8-inch channels, respectively. A diaphragm pump that can deliver up to 1200 mL/min was used to maintain steady flow through the fluidic network between two reservoir tanks. Water flows from an atmospheric tank with a high water level through the channel and into an atmospheric tank with a low water level while the diaphragm pump continuously recycles water from the low-level tank to the high-level tank. Pressure taps at the ends of the channel consist of 1/16-inch OD, 1/25-inch bore stainless steel tubing inserted in holes in the compression nuts within 1.5 mm of the face of the nut as shown in Fig. 2(b). The taps were installed so as to touch the coils of the spring for adequate fluidic contact and then plumbed to a manifold containing a diaphragm differential pressure transducer (Validyne DP103 model). The transducer set up consists of a sensitive diaphragm which moves and generates a voltage proportional to the difference between the pressures of the fluids on either side of the diaphragm. The differential pressure transducer is set up to measure the gauge pressure at either end of the channel by opening one end of the diaphragm to the atmosphere and the other end to either end of the channel flow by opening the appropriate valve as shown in Fig. 2(a). The pressure drop driving the flow is thus the difference in the gauge pressures at both ends of the channel. The analog voltage signal is carried through a model CDIS carrier demodulator to a Measurement Computing USB-1408FS that enables data collection through a LabView™ Virtual Instrumentation(vi) program. Distilled water
was used in the experiments. A machine-vision camera coupled with a telecentric lens and collimated back lighting of the spring was used for imaging during experiments.

**B. Channel hydrostatics**

Hydrostatic testing of the channel provides information about the channel compliance and static pressure limits and therefore the maximum pressure driving force for flow\textsuperscript{35}. Lowry and Thiessen\textsuperscript{37} had previously developed a theory for the static stability of free surfaces pinned on helical wire supports for zero Bond number scenarios. This theory can be useful for predicting the physical high and low pressure limits of the channel stability for low Bond number configurations such as geometries with small cross-sections in normal gravity\textsuperscript{35,38}. After coating, the spring was dismantled from the lathe and mounted in the hydrostatics/flow system. This system was bled thoroughly with distilled water and the channel connected to a water reservoir which was situated on a vertically adjustable stage. A specially designed stainless steel cup was made level to the center of the channel using the imaging system and the cup plumbed to the reservoir for fluidic contact. The reservoir was adjusted to the center of the installed channel by making the water meniscus in the steel cup flat with the sharply beveled tip of the cup (this ensures no extra interface pressure due to a curvature). Fig. 3 depicts the leveling procedure. This adjustment was taken as the zero of the pressure measurements. The reservoir was then carefully raised by 0.1 inch, the corresponding voltage allowed to stabilize for about 5 minutes and the channel allowed to further stabilize for another 5 minutes before full-channel image scans were acquired. This procedure was repeated until the channel blew out (leaked) due to a local failure.
C. Steady flow

A 6 to 10 point gravimetric calibration of the flow meters (the number of points depending on the flow meters) was performed prior to the flow experiment. After the hydrostatic image scans were acquired, the plumbing system was reconfigured for flow as shown in Fig. 2. The flow rate from the diaphragm pump was then set using a downstream valve which flows water through the flow meter connected before the injection tank (in order to further dampen any flow pulsation due to the pump). A 15-20 minute wait was observed to allow the levels in the two reservoirs to become steady (a good indication of steady flow). The gauge pressures (voltages) at the ends of the channel were also monitored (by turning the valve connection to the water side of the diaphragm) to ensure that they were steady thus serving as an independent indicator that the flow was steady. A movie scan of the channel in steady flow at 30 frames per second, for certain flow rates were then acquired similarly to the hydrostatic image scan. Independent voltage acquisition at 10 Hz for all the experimental flow rates were also recorded. Because of the strong dependence of slip length on viscosity and the dependence of water viscosity on temperature, temperature data was logged throughout the flow experiment. This was done by using thermocouples immersed three thermocouples to monitor the temperatures in the air and the two tanks. This data was logged using a custom LabView program. The experimental schematics are shown in Fig. 2 and Fig. 4. Experimental and systematic errors were propagated in this indirect measurement of slip length because of the intricacy involved. In this study the parameters whose measurement potentially contributes to the error are: the transducer measurements of voltage which implies pressure drop, flow rate, viscosity (through temperature changes during experiments), cross-section and length of channel. Voltage, temperature, outer channel and
wire diameters, length, gravimetric flow rate, and float image measurements were acquired and subjected to statistical data reduction. The errors were built into the dimensionless pressure gradient.

![DIagram](image)

**FIG. 5.** Diameter determination schematics.

### D. Image acquisition and analysis

A Basler digital camera with a telecentric lens and a collimated light source mounted on the same aluminum beam that goes under and is oriented perpendicular to the spring is
used for both still images and movies, as shown in Fig. 4. The telecentric lens assures that a silhouette of the spring is obtained without parallax. The image is brought to sharp focus by adjusting a micrometer screw on the mounting, after which still images or 10-30-second movies are acquired at 30 frames per second. Since the horizontal field of view with the telecentric lens is 1.44 in., the camera-lens-light assembly is carefully moved, by a predetermined amount for equal sized images, on a 1m long translational stage with a digital readout accurate to 1/10,000 in. In this way the whole length of the channel is scanned for still images or movies. Image analysis consists of analyzing still images from hydrostatics and movies obtained during flow. A custom MATLAB edge finding code which can find edges with sub-pixel resolution based on sharp transition in gray values was implemented to essentially find the projected diameter of the silhouettes that represent the channel at each axial position or column of pixels by finding the difference between the top and bottom edges of the silhouette (Fig. 5):

\[ D(z_i) = y_b(i) - y_t(i) \quad i = 1, \ldots, N_c \]

where \( N_c \) is the number of columns in the image and \( z_i \) is the horizontal coordinate of column \( i \) that is determined from the magnification calibration. To determine the compliance profile it is helpful to smooth the raw diameter profile using a spatial discrete Fast Fourier Transform (FFT) smoothing process to eliminate frequency components related to the periodicity of the coil itself. The raw diameter profile is first detrended by subtracting the best-fit line to the \( D(i) \) data

\[ \tilde{D}(z_i) = D(z_i) - \bar{D} - m(z_i - z_0) \quad i = 1, \ldots, N_c \]

where \( m \) is the slope of the best-fit line to the \( D(i) \) data and \( z_0 \) is the horizontal mid point of the image. The detrended diameter profile is Fourier transformed to give Fourier coefficients
and a smoothed diameter profile is then constructed by truncating the Fourier series using Lanczos smoothing\textsuperscript{39} to reduce the Gibb’s phenomenon.

\[ D_s(z) = \bar{D} + m(z - z_0) + \text{Re} \{c_1\} \]

\[ + \sum_{k=2}^{N} \sin(\pi(k - 1)/N)\text{Re} \{e^{i2\pi(k-1)(j-1)/N}\} \]  \hspace{1cm} (4)

The smoothed axial profiles for each image were then added to obtain the composite or whole channel profile. For the movies, the frames for the movie from each portion of the channel were averaged and the average diameters added to get the full channel profile during flow. A camera calibration was done using a standard calibration slide with markings spaced 0.5mm apart. This calibration is used to find the linear dimensions of the spring from images using the NIH freeware program ImageJ.

III. RESULTS AND DISCUSSION

A. Hydrostatic diameter profiles

Generally, for a given channel length and pitch, wire diameter and wetting property, the composite diameter (wire and meniscus) is expected to increase with hydrostatic pressure, and the channel is supposed to be stable within a pressure range for the given parameters. Fig. 6 shows the axial diameter profiles for different static pressures and different flow rates. The diameter is observed to increase at each axial point as the hydrostatic pressure is increased in steps of 0.1 in H\textsubscript{2}O. It is also observed that the separation between the static curves are fairly uniform. This suggests a good uniformity in the pitch of the spring. In a previous work with custom microsprings\textsuperscript{35} it was observed that static curves were closer together at some axial points (smaller pitches) and farther apart at others (larger pitches).
The nonuniformity in the profiles therefore reflect wetting variations along the channel. The wetting non-uniformities are due to coating technique imperfections and substrate-coating adhesivity issues. It is however fortunate that the wetting portions ($\theta_c < 90^\circ$) are of much shorter extent compared to the span of the channel making the channel essentially super-hydrophobic ($\theta_c > 150^\circ$). Therefore, the channel is expected to hold higher pressure than one with a wetting contact angle owing to the water repellence of the coating. The change in diameter with pressure is a measure of the channel compliance\textsuperscript{35}. Hydrostatic characterization of the channel by quantifying the average compliance along the channel due to local and temporal variations in pitch and wetting properties is an indirect method of estimating the contact angle and contact angle hysteresis of the surface. This estimate is done by a comparison of the local diameter vs. pressure data to the theory developed by Bernate and Thiessen\textsuperscript{35,38}. The more non-wetting portions of the hydrophobic channels are expected to be stiffer (less compliant) than the more wetting regions because the water would not wet the lower-energy substrate in the former case and so the diameter is expected to change less with change in pressure for a given pitch. Local failure is expected to occur at the most compliant point along the channel represented by the most wetting region or ends with higher than average pitch. Highly compliant channels are expected to have more roughness in the presence of a pressure gradient that drives the flow and consequently a reduced slip during flow. The hydrostatic characterization also serves to establish the stable pressure range (low and high pressure) that is achievable in the channels. This pressure range determines the gradient for flow and thus the maximum achievable flow rate in the capillary channel. Also, the hydrostatic calibration may be used to find the pressure profile during flow by comparing the hydrostatic and flow diameter profiles. Fig. 7 shows the average compliance ($dD/dP$) of
the same channel over the course of about two weeks. The variation of compliance in our channels and their character (contact angle and contact angle hysteresis) due to changing pitch or Bond number is reported in Chapter 6.

FIG. 6. Diameter profiles along a 1/4-inch spring axis from hydrostatic calibration for different static pressures and for different flows. Curves from bottom to top are for increasing static pressure. The static profiles are used to determine a global dependency of diameter on pressure and position from which the profile for flow is then estimated using the flow diameter profiles.
FIG. 7. Average compliance measurements for the same 1/4-inch spring over the course of several days ($L_c=14$ in., pitch $L=0.3$ or about 3 wire diameters). The stable pressure ranges for the different temporal measurements were reproducible to extents that did not vary much.

B. Flow diameter and pressure profiles

During flow, the diameter is expected to decrease downstream due to reduction in pressure in this direction. The diameter profile is expected to lie within the upper and lower limits of the hydrostatic profiles. A comparison of the hydrostatic and flow diameter profiles may then be used to generate the flow pressure profile. Fig. 8 shows pictures of the injection (highest pressure) and suction (lowest pressure) ends respectively for a 1/4-in. spring (Fig. 8
FIG. 8. Pictures showing (a) injection or highest pressure end and (b) suction or lowest pressure end in a 1/4-inch spring with a pitch $L=0.3$ for a flow rate of 628 mL/min. On close scrutiny, the meniscus appears more bulged out at the injection end (c) and (d) show respectively injection and suction ends for a 1/8-inch spring with a pitch of 0.72 at a flow rate of 32 mL/min. The difference in diameters is more obvious because of the larger pitch.

(a) and (b)) and a 1/8-in. spring (Fig. 8 (c) and (d)). It can be seen in this pictures that the menisci look more bulged-out at the injection ends for both spring sizes. The bulge looks more prominent in the case of the 1/8-inch spring because of the larger pitch. The smoothed axial diameter profiles for different flow rates are shown in Fig. 6. It is observed that the diameter decreases in the direction of flow and that this reduction is more rapid as flow rate increases. A measurable drag reduction is expected during flow because of
the Cassie-Baxter-like lubrication (fluid flow on shear-free air) occasioned by a combination of the chemical hydrophobicity of the wire and the large reduced-shear portions (liquid to air portions) of the stretched spring. An inspection of the pressure profile obtained from the flow diameter profiles and the hydrostatic calibrations reveals the extent of dissipation along the flow path. This is partly viscous dissipation due to fluid viscosity and partly form dissipation due to both wire penetration into the fluid in the more wetting sections of the channel and roughness due to the deformed air-water interface. The pressure profiles show the expected steeper gradients as flow rate is increased. However, there are pressure jumps (as seen in the bumps in the profiles especially at the ends). This could be due to dynamic pressure perturbations from the flow due to stagnation on the wires which can cause local jumps in pressure. In order to estimate the overall pressure drop across the channel from compliance measurements, a straight line was fitted to the pressure gradient data and an overall pressure drop estimated from same. These pressure drops were then compared to that measured directly by pressure taps at both ends of the channel (Table II). Table 1 shows

<table>
<thead>
<tr>
<th>( \dot{V} ) [mL/min]</th>
<th>From image</th>
<th>From transducer</th>
</tr>
</thead>
<tbody>
<tr>
<td>93.48</td>
<td>0.096</td>
<td>0.094</td>
</tr>
<tr>
<td>483.6</td>
<td>0.43</td>
<td>0.449</td>
</tr>
<tr>
<td>628</td>
<td>0.676</td>
<td>0.56</td>
</tr>
</tbody>
</table>

pressure drops measured from the images and from pressure taps for three different flow rates. The independent measurements are within a few percent of each other lending credence to the usefulness of the imaging technique for quantifying pressure gradient. However, concerns
FIG. 9. Pressure gradient along the channel axis for different flow rates in a 14-inch, 1/4-inch OD hydrophobized channel (aspect ratio 65, pitch L=0.3) (a) 93.48 mL/min and (b) 288.98 mL/min (c) 483.60 mL/min and (d) 628 mL/min. Note that the slope (pressure gradient) is steeper with increasing flow rate but so far unresolved jumps in the pressure profiles especially at the ends distort the overall pressure drop.

still remain about the yet unexplained distortions (jumps or d) in especially at the ends. A possible explanation is that the perturbation pressure (due to the alternating boundary conditions and the flow) is enough to deform the meniscus such that the meniscus is more bulged out where the pressure is higher and more sucked in where pressure is lower.
C. Transducer pressure drop data analysis

Pressure drop versus flow rate data taken from the diaphragm was reduced to pressure gradient. The pressure gradient data for the same channel over the Reynolds number range 84 to 2430 (equivalent to measured flow rates of 10-628 mL/min) were taken and compared to a full aspect ratio Finite Element Method (FEM) calculation results for different slip lengths to estimate any measurable experimental drag reduction. Fig. 10 is a plot of pressure gradient as a function of the Reynolds number for the quarter inch spring for 2 different aspect ratios of 32.4 and 64.8, and a similar pitch of 0.3. A comparison of the data to

FIG. 10. Pressure gradient vs Reynolds number for the quarter inch OD channel. The full aspect ratio FEM calculations for a slip length of 26 µm is shown in conjunction with data and theoretical results for laminar flow in a pipe of same ID as the channel.

FEM calculations for an effective slip pipe of the same ID and aspect ratio shows that the 2 aspect ratios have a identical slip lengths similar to 26 µm. The nonlinearity in the plot
for the smaller aspect ratio shows an expected prominent flow development effect. However, the plot for the larger aspect ratio of 64.8 (still < 100) is more linear and shows better developed flow. Also, since the data points are below the no-slip line even within limits of experimental error, there is more confidence in the measured slip length. To further clarify all the probable measurement errors, all other errors due to flow rate, viscosity, lateral and axial dimensions were built into a dimensionless pressure gradient. This is in order to clarify that there is actual and measurable slip because of the minuscule size of the phenomenon and the importance of accurate reporting. Inclusion of all these errors is shown in a plot of the dimensionless pressure gradient as a function of Reynolds number (Fig. 11). Fig. 11 shows the dimensionless pressure gradient as a function of Reynolds number for two different aspect ratio springs with the same pitch and with all the measurement errors accounted for. The data for the shorter spring in Fig. 11 a shows flow development as the data are farther away from the no-slip line than for the longer spring. Also the data for the longer spring (Fig. 11 b) are more evenly spread around the 26 µm line and also closer to the no-slip line showing better developed flow. The 1/8-inch spring is expected to show more slip because of its smaller lateral dimension and smaller hydrostatic pressure, thus less gravity induced roughness. Fig. 12 shows data for two different aspect ratios (111 and 172) and two different pitches (0.40 and 0.55). The pressure gradient data for the 2 cases are consistently below the no-slip line. The data for aspect ratio 111 and pitch 0.40 lie approximately between the FEM lines for a same aspect ratio, same ID pipe as the spring with effective slip lengths of 70 and 100 µm. Similarly, for the aspect ratio of 172 and pitch of 0.55 (same spring stretched), the data fall between 70 and 140 µm. These show that within limits of pressure drop measurement errors, the slip lengths measured fall within the reported range.
FIG. 11. Dimensionless pressure gradient (non-dimensionalized with respect to the fully-developed laminar flow closed pipe pressure gradient) vs. Reynolds number, Re for quarter inch OD spring (a) $L_c=7$ in., aspect ratio of 32.4 and pitch of 0.3 and (b) $L_c=14$ in., aspect ratio of 64.8 and pitch of 0.3. The dash-dot lines in both cases represent FEM calculations of the dimensionless pressure gradient for the same aspect ratios of a pipe with an effective slip of 26 $\mu$m on its wall and the solid horizontal at 1 is the no-slip line. Note the similarity between this plot and Fig. 10. The shorter channel shows flow development (the data points are farther away from the no-slip line).

These measurements are within the ranges that have been reported in extant literature for confined channels (see Table II). Fig. 13 shows the pressure gradient normalized using the no-slip laminar pressure gradient, as a function of Reynolds number. Fig. 13(a) shows data for aspect ratio 111 and pitch 0.4 shows appreciable slip within experimental error (data below the no-slip line at 1). The data are scattered between the dash-dot and solid lines representing slip lengths of 70 and 100 $\mu$m indicating that the measurements are in this range within measurement errors. Also, as expected, data for the larger pitch of 0.55 and aspect ratio of 172 show larger slip lengths of 70 and 140 $\mu$m. This is mainly due to the
FIG. 12. Pressure gradient vs Reynolds number for the 1/8-inch OD channel. The full aspect ratio FEM calculations for a slip lengths of 70 -140 µm and theoretical results for laminar flow in a pipe of same ID as the channel are shown in conjunction with data.

larger proportion of shear-free water-air interface between the wires. Fully-developed flow model calculations using experimental parameters (160° contact angle, wire radius, pitch, average channel pressure and Reynolds number) yielded slip lengths between 41 and 132 µm for the channel with aspect ratio of 111 and pitch of 0.37 and 223 and 365 µm for aspect ratio of 172 and a pitch of 0.55.

D. Implications for practical applications

One of the envisaged use of these channels is for liquid gas contacting in microgravity environments. The flow achieved in the 1/8-inch and 1/4-inch springs are 93.4 mL/min and 628 mL/min respectively. For square pitch packings of these springs, these translate to very high liquid mass velocities. For a 1/8-inch spring on a 1/4-inch spacing, the liquid mass ve-
FIG. 13. Dimensionless pressure gradient (non-dimensionalized with respect to the fully-developed laminar flow closed pipe pressure gradient) vs. Reynolds number, Re for 1/8-inch OD spring (a) $L_c=11$ in., aspect ratio of 111 and pitch of 0.40. The full and the dash-dot lines are same aspect ratio FEM calculations for pipes with effective slips of 70 and 100 µm respectively (b) $L_c=17$ in., aspect ratio of 172 and pitch of 0.55. The full and the dash-dot lines are same aspect ratio FEM calculations for pipes with effective slips of 70 and 140 µm respectively.

Velocity is 28406 lb/hr ft$^2$ and for the 1/4-inch spring on a 1/2-inch spacing the mass velocity is as high as 47748 lb/hr ft$^2$. Absorption rates of CO$_2$ by 1 M NaOH solution of about 1 mL/s has been demonstrated in a 1/8-inch diameter spring$^{38}$. Furthermore, the significant slip lengths measured, in the range 26-140 µm (0.0095-0.11, normalized with respect to the channel radius) are in the high end measured in the literature (Table I). This makes the springs potentially useful for drag reduction in fluidic networks.
IV. CONCLUSIONS

Water was successfully flowed at flow rates of up to 628 mL/min and 93.5 mL/min through 1/4-inch and 1/8-inch springs respectively. Imaging and transducer data were used to quantify pressure drop as a function of flow rate with comparable results for both methods in some cases. The cases where the two measurements were not comparable could be due to meniscus deformation due to possible pressure stagnations on the wire. A comparison of transducer pressure drop data with Poiseuille flow predictions showed a reduction in pressure drop for the channels with alternating slip and no slip boundary compared to a close pipe, within limits of experimental error. A further comparison of normalized pressure gradient data with finite element effective slip model revealed a slip lengths in the vicinity of 26 µm for the 1/8-inch spring with a normalized pitch of 0.3, in the range 70 to 100 µm for 1/8-inch spring with normalized pitch of 0.37 and a range of 70 to 140 µm for a 1/8-inch with a normalized pitch of 0.55. These slip lengths are within the significant slip length range reported in the extant literature. The slip lengths measured for the 1/8-inch are in the high range (50 to 400 µm) measured in the extant literature. This investigations suggests that more stable and significantly higher flows, and higher slip lengths could be measured in the same channels in microgravity (one of the envisaged application environment for these channels). This is because of the reduced gravitational pull which results in a more stable channel and reduced roughness (even a perfectly cylindrical meniscus). Because of the reduced gravity, larger cross-sections, larger flows and thus higher Reynolds numbers may be achieved. Also, a more robust coating, for instance by using adhesion promoters, better coating techniques or better coating materials will reduce the risk of local wetting failures and lead to better stability and more drag reduction even in normal gravity.
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REFERENCES


36 D. Thiessen, J. Oelerich, K. Cline, and L. Zhang, “Hydrostatics, steady flow, and dynamics in helically-supported capillary channels,” 62nd Annual Meeting of the APS Division of
Fluid Dynamics 54, Minneapolis, MN (2009).


ATTRIBUTION

This page contains information about the contribution of each of the authors on the manuscripts with multiple authors. In all of the manuscripts listed below, the first author was the main contributor in terms of conceptualizing, experimentation, analysis and writing, while the other authors contributed in varying degrees to the completion of the paper.


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The authors were international collaborators who helped in study design and implementation and also provision of supplementary data.
Manuscript 2: A Tale of Two Pedagogies – Comparing Lecture and Active Learning in a Fluids and Heat Transfer Class

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Manuscript 4: Flow in helical channels with periodic slip and no-slip boundaries.

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The second author contributed immensely as the Principal Investigator to the conceptualization of the study, and data analysis.

Manuscript 5: Hydrostatic stability in springs with highly water-repellent walls in normal gravity.

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Manuscript 6: Drag reduction for flow in superhydrophobic springs.

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