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Effectiveness of Hands-on Desktop Learning Modules to Improve Student Learning in Fluid Mechanics and Heat Transfer across Institutions and Program Types*

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Low-cost desktop learning modules (DLMs) were created to aid in student comprehension of a variety of engineering concepts. The DLMs are hands-on apparatuses that can be used to represent the theories behind the many process units seen in the industry. Activities associated with these modules may be used as a supplement to lecture materials. DLMs have initially been found to be effective within a classroom setting. Furthermore, intensive awareness has been gained through presenting results in reputable journals and conferences. However, the pedagogy associated with DLMs will not reach its full potential without translating to or propagating within the creator and outside institutions. To examine the translatability and disseminability of the DLMs, the modules were implemented in the chemical and mechanical engineering courses at several universities. In this paper, student assessment results from those beta implementations are discussed in light of several learning theories including Bloom's taxonomy and cognitive load theory. Moreover, the various aspects of DLMs including ease of use, flexibility, and complexity were evaluated by an expert panel composed of professors who teach transport phenomena-related courses to meet the adoption criteria of a new teaching/learning method. Results indicate that, regardless of the variation in the learning environment and implementation procedures, DLMs are useful for understanding key fluid mechanics and heat transfer concepts. Furthermore, the majority of the experts surveyed for this study are in favor of incorporating DLMs into the classroom. Based on these results, we expect DLMs will gain widespread interest and will be useful across curricula.

Keywords: desktop learning modules; hands-on apparatuses; venturi meter; heat exchangers; learning assessment

1. Introduction

The gap between engineering research and practice is universally recognized [1]. Engineering education suffers from the same paradigm where student comprehension of real-world practices is limited by available teaching methods. The use of alternative and complimentary learning methods to aid in student comprehension of engineering concepts has been explored for the past several decades. While dissemination and implementation (D&I) research is a growing area of science focused on overcoming the science-practice gap by targeting the distribution of information and adoption of

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interventions such as in public health and clinical practice settings [2], broader dissemination and adoption of new methods remains a challenge especially in the field of engineering [3].

Although the terms "propagation" and "dissemination" are commonly used interchangeably, they act as two separate steps that lead to the overarching goal of adoption. Dissemination is the sharing of methods through, for example, presentations, publications, and workshops, while propagation is the successful use of these disseminated methods by individuals at institutions and/or disciplines outside of those in which the innovation was first implemented. Seminars, online platforms, and instructional videos are a few methods considered to ease the transition of a new implementation strategy into the course curricula at beta institutions. Hands-on interactive group learning is one such method that engenders more student engagement than passive lecture due to its potential for being more applicable for engineering students [4], as the majority of these students tend to be active or kinesthetic learners [5]. Several works describe the learning gains achieved by hands-on learning in addition to our work at Washington State University (WSU) [6–12]. Much of the learning effect can be explained through Kolb's experiential learning model [13]. Kolb suggests that significant learning is more likely to occur when a person goes through a cyclical process. This consists of new concrete experiences, such as being introduced to a new piece of equipment or process, followed by reflection, which leads to abstract conceptualization and generalization, which, when tested empirically through active experimentation, leads to another new experience to continue the cycle. DLMs provide in-class opportunities for instructors to guide students through Kolb's learning cycle and for students to interact with a working model in which the theories they are learning are embedded and test their hypotheses regarding applications of these theories.

To support the hands-on mode of learning, low-cost DLMs were created at WSU with which engineering students can conduct experiments to learn fundamental principles of fluid mechanics and heat transfer. With a target cost comparable to a textbook, low-cost experiments make it possible for teams of students to pursue their investigations of fluid mechanics and heat transfer phenomena. The units are small enough for the desktop, require only hot and/or cold water, and are battery-powered, therefore they can be brought into the standard classroom [6] or even used to do assignments at home or within a distance education context [14], which heretofore has suffered from the paucity of lab experience and depending almost entirely on on-line lectures and/or web-interfaces [15].

Although the DLMs have great potential, without the ability to translate to other environments, the concept remains obscure with no tangible impact on the broader community. Through the years of testing at WSU, the DLMs have gained awareness and understanding within the engineering education community, but the next step requires propagation to outside institutions including universities, community colleges, two-year degree programs, and ultimately, even high schools. Three steps are required to completely disseminate a project: awareness, understanding, and action [16]. According to Harmsworth et al. [16], dissemination is the sharing of methods, while dissemination and implementation, or more appropriately propagation, involves the success of such methods by instructors outside the group who initiated the approach. Outreach activities such as journal articles, conference presentations, online platforms, and instructional videos are examples of methods that can be used to raise awareness and initiate the integration of new techniques into existing curricula. These outreach activities in themselves generally do not lead to the propagation and sustained adoption where consistent and widespread adoption typically requires higher levels of engagement. Hands-on technical training such as workshops with hands-on experience is generally a more effective strategy that promotes adoption [17]. Moreover, it is important to improve the characteristics of the innovation itself; design considerations should include relative advantage, compatibility, usability, complexity, and adaptability. Developers must also consider the factors that can impact widespread adoption such as management support, logistical issues, cultural differences, ease of use, and integration with existing curricula. Because every teacher, student, and classroom is different, building adaptability into the innovation allows for adoption to a wider audience as the new materials can be made to be compatible with existing pedagogy. Many conceptual frameworks for guiding dissemination and implementation research, such as the reach, effectiveness, adoption, implementation, and maintenance (RE-AIM) model [18], have been developed and are being tested especially for translating research into practice.

The purpose of this work is to evaluate the effectiveness of an initial DLM propagation effort in extending the pedagogy to early adopters. We first provide a framework for successful implementations based on the interdisciplinary research area referred to as 'diffusion of innovations' by Rogers [19]. We then view the effort in light of this framework, beginning with implementation support, and moving to the rather obvious index of effectiveness of the use of the innovation in enhancing student understanding. We conclude with a survey where we ask faculty directly about some of the criteria that are important in promoting the adoption of the new pedagogy and evaluate our efforts in light of research on what makes adoption of new strategies effective.

2. Theoretical Background

2.1 Diffusion of Innovations for Adoption

Rogers' model on the diffusion of innovations can be applied to evaluate the acceptance of an open educational resource developed by higher education faculty [19]. The adoption of an innovation is analogous to the process of diffusion and thus takes place over time. The process of diffusion involves five steps: Knowledge – awareness of the innovation but lacking complete information about it; Persuasion – growing interest and information seeking; Decision – deciding whether or not to try the innovation based on present and future situations for a faculty member (the process may end here if there is a negative decision); Implementation – making use of the innovation (if the user does not continue, this is called "reneging" on adoption); and Adoption – continued full use of the innovation. Currently, for our DLMs, we are in the final step of the diffusion process. Therefore, one of the goals in this paper is to check the acceptance of our DLMs against adoption criteria. According to Rogers' model, there are five independent variables that influence the rate or level of adoption of a given innovation [19]: perceived attributes of the innovation, type of innovation-decision, communication channels, nature of the social system, and the extent of the change agents' promotion efforts. Within the perceived attributes of the innovation, there are two subcategories of direct relevance: compatibility and complexity. Compatibility refers to the consistency of the innovation with the values, experiences, and needs of the potential adopter; while complexity refers to the perceived, or actual, difficulty of adopting the innovation. Rogers explains that the higher the perceived complexity, the lower its rate of adoption. Adoption of innovation must also be supplemented by gaining feedback, adjusting the innovation to fit a given context, and providing ongoing faculty support [20-23]. Therefore, to evaluate the adoption of DLMs, we conducted a faculty survey with thirteen questions focusing on compatibility and complexity attributes of DLMs.

2.2 Learning Processes

Learning theories, designed to identify different stages of learning development [24], are employed as a method of describing the types of behaviors we would like learners to demonstrate [25]. In this work, assessments and activities were designed following Bloom's taxonomy to promote deeper levels of thought with DLM experiments versus lecture alone. Here, we assess the results within the context of common foundational learning theories including Bloom's taxonomy, the ICAP (interactive, constructive, active and passive) hypothesis, information processing theory, and cognitive load theory.

Developed in 1956, Bloom's taxonomy [26] is the earliest and one of the most predominant theoretical learning frameworks used to classify higher-order learning. The framework originally consisted of six categories of cognitive processes that increase in complexity. In 2001, a revised taxonomy was developed [27, 28] such that learning objectives were described as actions leading to learner outcomes to include Remember, Understand, Apply, Analyze, Evaluate, and Create. Higher-order learning comprises "Apply", "Analyze", "Evaluate", and "Create" categories requiring deeper levels of thinking than basic knowledge acquisition and understanding. Using the DLM pedagogical method, we aim to teach in ways that transform student learning environments to be more effective, relevant, interactive, motivational, and experiential rather than simple information transfer. Therefore, DLM exercises and questions were developed and categorized within the higher Bloom's levels so that student understanding of the subject matter associated with DLMs is promoted and assessed.

To supplement our use of Bloom's taxonomy, multiple models were applied that seek to define the learning process. One such framework that aims to address the concept of "active" learning is the ICAP hypothesis [29]. According to the ICAP hypothesis, when students interact with peers and/or physical or virtual technology through interactive engagement, the largest learning gains will be observed; however, improvements in learning are seen in all three modes of active learning (interactive, constructive and active) compared to passive learning alone [30]. In a typical classroom, when students simply listen or take notes during a lecture, a more passive engagement proceeds where new information is stored but is less likely to be integrated with existing knowledge.

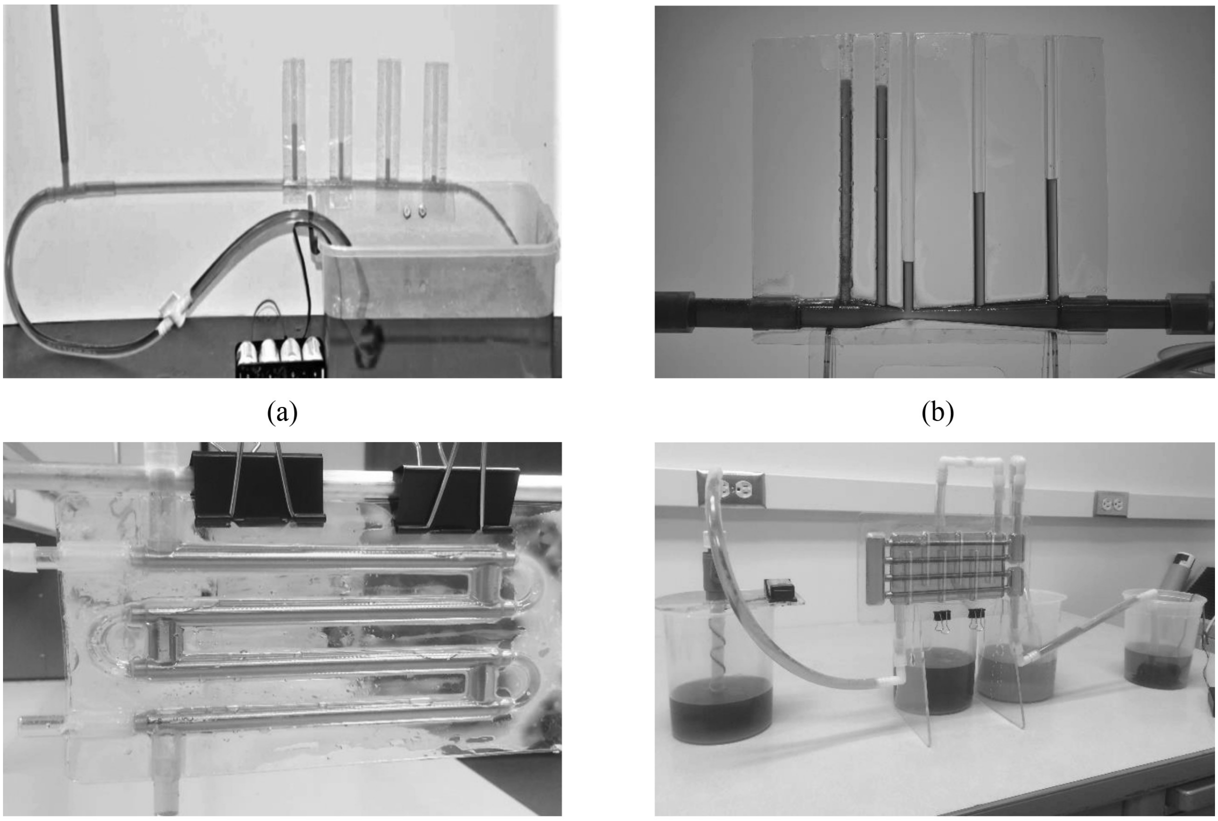
Another widely accepted learning model we must consider in our analyses is information processing theory (IPT) [31], which primarily concentrates on the processes of memory encoding and knowledge retrieval [32]. The underlying principle is that human minds behave like a computer in that the mind receives input, processes it, then delivers an output or that people simply respond to stimuli. This system is used to explain how a student learns information and retains it over a long period. The more organized this information is, the easier it is to process in the working memory, resulting in increased memory retention and schema construction because of easier integration of knowledge within the mind [33]. However, working memory can be exhausted easily because of its limited capacity (3–4 concepts or ideas at a time) [34]. The burden placed on the working memory throughout the learning process is referred to as cognitive load. Cognitive load theory (CLT), a framework developed in the 1980s [35], characterizes the human mind as an information processing system and provides a measure of cognitive load faced by a learner during new information processing. According to CLT, when a student receives new information, it contributes to three different additive types of cognitive load: intrinsic load, extraneous load, and germane load [36]. For effective learning and information processing, the combination of all types of loads must not exceed the limits of the individual's working memory.

Generally, understanding of fluid mechanics and heat transfer concepts offer extensive amounts of cognitive load to the learners because of the very complex nature of the problems. Therefore, the primary purpose of DLM use in the classroom in conjunction with lecture is to effectively manage load in the working memory by making the subject matter more visible, relevant and practical. Furthermore, introduction of DLMs in addition to lectures will engage students more in active, constructive, and interactive learning modes.

3. Materials and Methods

3.1 Desktop Learning Modules

Four different low-cost desktop learning modules (DLMs) were created with the goal of promoting student understanding of various transport phenomena. The hydraulic loss module (Fig. 1a) and venturi meter (Fig. 1b) were built to aid in fluid mechanics related concepts, while the double pipe (Fig. 1c) and shell & tube (Fig. 1d) heat exchangers were designed to aid in heat transfer related concepts. These DLMs were manufactured by vacuum forming over a 3D printed mold [6]. Once the hardware geometry was defined, the computer aided design was developed in SolidWorks^{TM} from which a 3D printed mold (one half of the



(a) (b) (c) (d)

Fig. 1. Desktop learning modules: (a) hydraulic loss system, (b) venturi meter, (c) double pipe heat exchanger, and (d) shell & tube heat exchanger. The developed DLMs are miniaturized, lightweight, see-through, simple, and safe for carrying out desktop experiments. All the accessories including pumps, battery, beakers, and tubing are off-the-shelf items, ensuring easy replacement.

Table 1. Brief description of DLM implementations

Univ., Dept., Semester, Course no., Course Title, (Number of students)	DLM type	Place of experiment	DLM setup	Pre- and posttest	Identification
UK, Lexington, ChE, F2017, CME 330, Fluid Mechanics, (43)	Hydraulic loss system	Lab	Students	In class	UK-Lex-F17
WSU, Pullman, ChE, S2018, CHE 332, Fluid Mechanics and Heat Transfer (25)		Class	Research assistant		WSU-S18
UK, Paducah, ChE, F2017, CME 330, Fluid Mechanics (29)				Out of class	UK-Pad-F17
UK, Paducah, ChE, F2018, CME 330, Fluid Mechanics (22)					UK-Pad-F18
UK, Lexington, ChE, F2018, CME 330, Fluid Mechanics (47)				In class	UK-Lex-F18A
UK, Lexington, ChE, F2018, CME 330, Fluid Mechanics (42)		Lab	Students		UK-Lex-F18B
WSU, Pullman, ME, S2017, ME 303, Fluid Mechanics (38)		Class	Research assistant		WSU-S17
UK, Lexington, ChE, F2017, CME 330, Fluid Mechanics (44)	Venturi meter	Lab	Students		UK-Lex-F17
WSU, Pullman, ChE, S2018, CHE 332, Fluid Mechanics and Heat Transfer (36)		Class	Research assistant		WSU-S18
UK, Paducah, ChE, F2017, CME 330, Fluid Mechanics (25)				Out of class	UK-Pad-F17
UK, Paducah, ChE, F2018, CME 330, Fluid Mechanics (22) (25)					UK-Pad-F18
UK, Lexington, ChE, F2018, CME 330, Fluid Mechanics (49)				In class	UK-Lex-F18A
UK, Lexington, ChE, F2018, CME 330, Fluid Mechanics (44)		Lab	Students		UK-Lex-F18B
WSU, Pullman, ME, S2017, ME 303, Fluid Mechanics (45)		Class	Research assistant		WSU-S17
WSU, Pullman, ME, S2017, ME 304, Heat Transfer (66)	Double pipe				WSU-S17
U. Idaho, Moscow, ChE, S2017, ENGR 320, Thermodynamics and Heat Transfer (29)					UI-S17
WSU, Pullman, ChE, S2018, CHE 332, Fluid Mechanics and Heat Transfer (26)	Shell & Tube				WSU-S18
UCO, ME, F2016, ENGR 4123, Heat Transfer (19)					UCO-F16

DLM) was created in a uPrint SE Plus 3D printer (Stratasys, Eden Prairie, MN) using ABSplus polymer. Next, vacuum forming was done over the 3D printed mold in a Centroform EZFORM1 SV 1217 Tabletop Vacuum Forming Machine with 0.02-inch thick PETG plastic. This results in one half of the DLM. Finally, the two halves of the vacuum formed DLM parts were glued together with acrylic adhesive (SCIGRIP 40) to produce the hydraulic loss and venturi DLMs [37]. However, extra steps were required for the heat exchanger DLMs. For the double pipe heat exchanger, the two halves were assembled together with four internal tubes (Fig. 1c); while for the shell & tube heat exchanger, the two halves were joined together with four internal tubes and six baffles (Fig. 1d). For both heat exchangers, the tubes were made of 304 stainless steel (McMaster-Carr) which were cut to length by hand with a tubing cutter. For the shell & tube heat exchangers, baffles were produced by cutting 1/8th inch thick PETG sheets (McMaster-Carr) with a water jet. The manufacturing process used here is fast, reliable, flexible, and cheap, which makes it ideal for DLM production at the host and adopted sites.

3.2 Implementations

This study involves chemical and mechanical engineering undergraduate students, either juniors or seniors, from different universities who are enrolled in fluid mechanics and heat transfer courses. We have beta tested four DLMs, a hydraulic loss system, venturi meter, and double pipe and shell & tube heat exchangers, at different campuses of several universities including Washington State University (WSU), Pullman, the University of Idaho (UI), Moscow, the University of Central Oklahoma (UCO), Edmond and two campuses of the University of Kentucky, Lexington (UK-Lex) and Paducah (UK-Pad). Briefly, students first go

Table 2. Statistics on hydraulic loss module

Question	Implementation site	Mean ± Std. Deviation		P-value, p	Effect Size, d
		Pretest	Posttest		
Q1. Pressure profile in suddenly expanded-contracted pipe	UK-Lex-F17	3.02 ± 4.26	3.16 ± 3.50	0.846	0.04
	WSU-S18	2.88 ± 3.88	3.68 ± 4.11	0.179	$0.20^{\#}$
	UK-Pad-F17	3.45 ± 4.10	2.69 ± 3.18	0.291	$-0.21^{\#}$
	UK-Pad-F18	5.00 ± 4.65	8.00 ± 3.81	0.044*	$0.71^{\#\#}$
	UK-Lex-F18A	2.64 ± 4.07	3.70 ± 4.19	0.176	$0.26^{\#}$
	UK-Lex-F18B	4.90 ± 4.62	5.29 ± 4.46	0.602	0.09
	WSU-S17	6.21 ± 4.43	4.90 ± 4.07	0.082	$-0.31^{\#}$
Q2. Velocity profile in straight pipe	UK-Lex-F17	2.09 ± 4.12	3.95 ± 4.95	0.044*	$0.41^{\#}$
	WSU-S18	6.00 ± 5.00	8.80 ± 3.32	0.005**	$0.69^{\#\#}$
	UK-Pad-F17	2.40 ± 4.35	5.90 ± 5.01	0.010**	$0.75^{\#\#}$
	UK-Pad-F18	2.70 ± 4.56	9.50 ± 2.13	<0.001**	$2.20^{\#\#\#}$
	UK-Lex-F18A	0.90 ± 2.82	1.90 ± 3.98	0.096	$0.30^{\#}$
	UK-Lex-F18B	2.40 ± 4.31	5.20 ± 5.05	0.002**	$0.60^{\#\#}$
	WSU-S17	0.53 ± 2.26	2.11 ± 4.13	0.012*	$0.52^{\#\#}$
Q3. Pressure profile in straight pipe	UK-Lex-F17	3.95 ± 4.95	6.28 ± 4.89	0.003**	$0.47^{\#}$
	WSU-S18	7.60 ± 4.36	6.80 ± 4.76	0.538	–0.18
	UK-Pad-F17	4.10 ± 5.01	3.80 ± 4.94	0.769	–0.06
	UK-Pad-F18	3.20 ± 4.77	8.20 ± 3.95	<0.001**	$1.20^{\#\#\#}$
	UK-Lex-F18A	4.30 ± 5.00	4.30 ± 5.00	1.000	0.00
	UK-Lex-F18B	5.00 ± 5.06	4.80 ± 5.05	0.812	–0.04
	WSU-S17	3.42 ± 4.81	3.42 ± 4.81	1.000	0.00

* and ** indicate significance at the 95% and 99% confidence levels, respectively. #, ## and ### indicate small ($0.2 \le d < 0.5$), medium ($0.5 \le d < 0.8$) and large ($d \ge 0.8$) effect sizes, respectively.

through in-class lecture(s) on related topics and then take the pre-test. After that, they conduct the corresponding DLM experiment as a team of 4 or 5 students. A short lecture on the experimental methodology is provided by the teaching assistant or the instructor after which each team conducts the experiment guided by a worksheet in which they collect data. Following the experiment, students complete the worksheet calculations using their data, and finally, they take a posttest comprised of similar materials as that on the pretest. However, depending on resource availability, some variations occurred between implementations. For example, most instructors carried out the DLM experiment in a classroom environment; whereas others experimented in a lab environment. A summary of the implementations including university, department, course, number of students in the class, DLM type, and the variations between implementations are provided in Table 1.

3.3 Sample Pre and Posttest Assessment Questions

A set of pre and posttest questions were developed that correlate concepts taught in traditional fluid mechanics and heat transfer courses. To measure changes in conceptual understanding, these questions were administered before (pretest) and after (posttest) the LCDLM activity. The number of questions ranges from three to six depending on the type of DLM. The complete set of questions for each DLM can be found in Appendix A.

3.4 T-Test Analysis and Effect Size

A two-sided paired sample t-test analysis was carried out with the hypothesis defined as follows:

Null hypothesis:

Mean of posttest = mean of the pretest

Alternative hypothesis:

Mean of the posttest ≠ mean of the pretest

In this paper, the effect size is reported as Cohen's d where d is defined as:

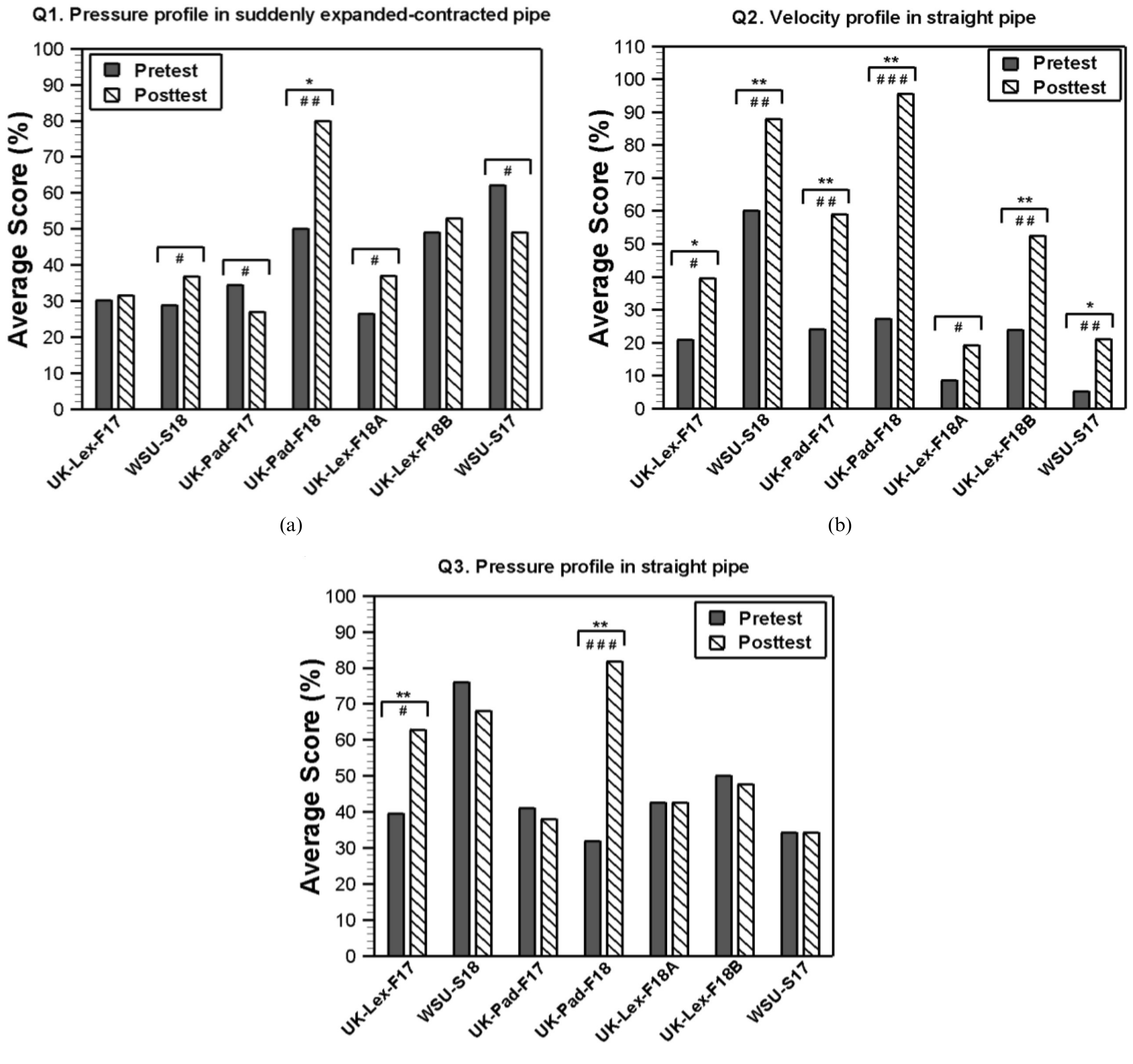
$$d = \frac{Mean_{post} - Mean_{pre}}{s}.$$

The pooled standard deviation s can be given as:

$$s = \sqrt{(s_{post}^2 + s_{pre}^2)/2}.$$

4. Results

Figs. 2–5 and Tables 2–5 provide a comparison between the pre and posttest results for the DLM implementations as described in Table 1. We discuss results for each of the DLMs individually to compare improvements in conceptual understanding due to implementations of DLMs in class.



(a) (b)

(c)

Fig. 2. Statistical analysis of pre- and posttest results for hydraulic loss DLM implementations at different universities/disciplines for different questions. The number of data points is $N = 43$ for UK-Lex-F17, $N = 25$ for WSU-S18, $N = 27$ for UK-Pad-F17, $N = 22$ for UK-Pad-F18, $N = 47$ for UK-Lex-F18A, $N = 42$ for UK-Lex-F18B and $N = 38$ for WSU-S17. * and ** indicate significance at the 95% and 99% confidence levels, respectively. #, ## and ### indicate small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$) and large ($d \geq 0.8$) effect sizes, respectively.

4.1 DLMs for Fluid Dynamics

A hydraulic loss module and a venturi meter were implemented seven times in the chemical and mechanical engineering disciplines at three universities, UK at Paducah and Lexington, and WSU Pullman. These DLMs are selected to confront important misconceptions in fluid flow through pipes and ducts.

4.1.1 Hydraulic Loss Module

Results for the hydraulic loss module are summarized in Fig. 2 and Table 2. In Question 1 in which students were asked to select the correct pressure vs axial location profile in a suddenly expanded then contracted pipe (Fig. 1a), no statistical difference ($p > 0.05$) between pre-test and posttest scores has been observed except in one implementation at UK-Pad-F18. The UK-Pad-F18 implementation shows a statistical improvement at a 95% confidence level ($p = 0.044$) with a medium effect size ($d = 0.71$).

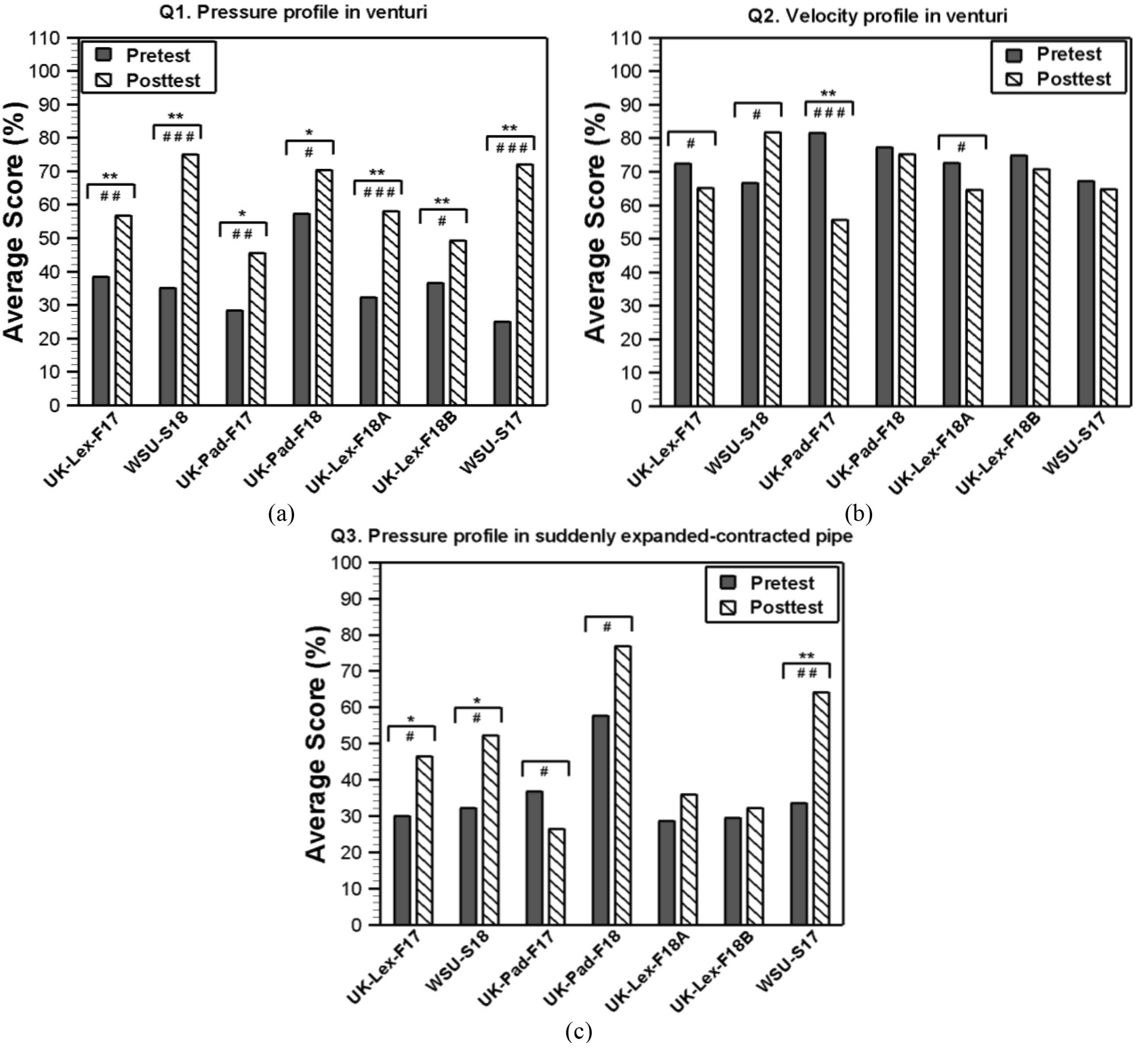
On the second question on selection of the correct velocity vs axial location for flow through a pipe, significant improvements are noted (Fig. 2b and Table 2) in all implementations with at least a 90% confidence level. Among seven independent implementations, four implementations show improvement with a confidence level greater than 99% ($p \leq$

0.01) and medium to large effect sizes (d = 0.60 to 2.20), two implementations show improvement with a confidence level between 95% to 99% (0.01 < p ≤ 0.05) and small to medium effect sizes (d = 0.41 and 0.52), and only one implementation shows improvement with a confidence level between 90% to 95% ($0.05 < p \leq 0.1$) with a small effect size (d = 0.30).

For Question 3, pressure vs axial location down the pipe, only in the cases involving UK-Lex-F17 and UK-Pad-F18 (Fig. 2c) we see convincing statistical improvements with a confidence level higher than 99% ($p < 0.01$) with moderate (d = 0.47) and very large (d = 1.2) effect sizes, respectively. For the other five implementations, no statistically significant differences were obtained between pre- and posttest results. Surprisingly, in two cases (UK-Lex-F18A and WSU-S17), we see the same score before and after the DLM implementation leaving $p = 1.000$ and $d = 0.00$.

4.1.2 Venturi Module

Assessment data associated with the venturi meter implementations are summarized in Fig. 3 and Table 3. Results for Question 1 relating to the selection of the most realistic graph depicting pressure vs axial location show significant improvement from pre-test to posttest with 99% ($p \leq 0.01$) or at least 95% ($0.01 < p \leq 0.05$) confidence throughout the implementations over the various



(a) (b) (c)

Fig. 3. Statistical analysis of pretest and posttest of Venturi DLM implementations at different universities for different questions. Note that, in Fig. 3c, the question in WSU-S17 implementation was different from other universities substituting with a question about the physical meaning of Bernoulli's equation (see Appendix A). The number of data points is $N = 43$ for UK-Lex-F17, $N = 25$ for WSU-S18, $N = 25$ for UK-Pad-F17, $N = 22$ for UK-Pad-F18, $N = 47$ for UK-Lex-F18A, $N = 42$ for UK-Lex-F18B and $N = 38$ for WSU-S17. * and ** indicate significance at the 95% and 99% confidence levels, respectively. #, ## and ### indicate small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$) and large ($d \geq 0.8$) effect sizes, respectively.

Table 3. Statistics on venturi module

Question	Implementation site	Mean ± Std. Error		P-value, *p*	Effect Size, *d*
		Pretest	Posttest		
Q1. Pressure profile in venturi	UK-Lex-F17	3.84 ± 2.92	5.68 ± 3.73	0.006**	$0.56^{\#\#}$
	WSU-S18	3.50 ± 3.98	7.50 ± 3.43	<0.001**	$1.10^{\#\#\#}$
	UK-Pad-F17	2.84 ± 2.63	4.56 ± 3.97	0.036*	$0.53^{\#\#}$
	UK-Pad-F18	5.72 ± 3.26	7.04 ± 2.51	0.037*	$0.46^{\#}$
	UK-Lex-F18A	3.22 ± 2.99	5.80 ± 3.43	0.000**	$0.81^{\#\#\#}$
	UK-Lex-F18B	3.66 ± 2.81	4.93 ± 3.26	0.008**	$0.42^{\#}$
	WSU-S17	2.49 ± 2.77	7.20 ± 2.69	<0.001**	$1.70^{\#\#\#}$
Q2. Velocity profile in venturi	UK-Lex-F17	7.25 ± 2.89	6.52 ± 3.43	0.113	$-0.23^{\#}$
	WSU-S18	6.67 ± 3.82	8.17 ± 3.09	0.104	$0.44^{\#}$
	UK-Pad-F17	8.16 ± 2.15	5.56 ± 4.10	<0.001**	$-0.87^{\#\#\#}$
	UK-Pad-F18	7.72 ± 2.49	7.52 ± 1.30	0.689	–0.11
	UK-Lex-F18A	7.27 ± 3.21	6.45 ± 3.02	0.168	$-0.26^{\#}$
	UK-Lex-F18B	7.48 ± 3.27	7.07 ± 3.35	0.425	–0.12
	WSU-S17	6.73 ± 3.24	6.47 ± 2.53	0.690	–0.09
Q3. Pressure profile in suddenly expanded-contracted pipe	UK-Lex-F17	3.00 ± 4.30	4.64 ± 4.39	0.050*	$0.38^{\#}$
	WSU-S18	3.22 ± 4.28	5.22 ± 4.59	0.027*	$0.45^{\#}$
	UK-Pad-F17	3.68 ± 4.31	2.64 ± 3.55	0.333	$-0.27^{\#}$
	UK-Pad-F18	5.76 ± 4.48	7.68 ± 3.86	0.100	$0.46^{\#}$
	UK-Lex-F18A	2.86 ± 4.00	3.59 ± 4.42	0.357	0.17
	UK-Lex-F18B	2.95 ± 4.28	3.32 ± 4.56	0.706	0.08
Q4. Bernoulli equation	WSU-S17	3.36 ± 3.83	6.42 ± 4.16	<0.001**	$0.77^{\#\#}$

* and ** indicate significance at the 95% and 99% confidence levels, respectively. #, ## and ### indicate small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$) and large ($d \geq 0.8$) effect sizes, respectively.

departments and institutions. Moreover, as shown in Fig. 3a and Table 3, this particular question shows high ($d \geq 0.8$) or at least moderate ($0.50 \leq d < 0.80$) effect sizes in five implementations among the seven. The effect size in the other two implementations, UK-Pad-F18 and UK-Lex-F18B, are $d = 0.46$ and 0.42, respectively, which are very close to the moderate range.

In Question 2 (Fig. 3b), students were asked about the velocity profile relative to the axial location of the venturi. Statistics for this question show ambiguous results from one implementation to another. For instance, implementation results from WSU-S18 show improvement from pre- to posttest with a small effect size ($d = 0.44$) though not statistically significant ($p > 0.1$), while implementation at UK-Pad-F17 shows a significant decrease ($p < 0.01$) in understanding with large effect size ($d = -0.87$). Surprisingly, all other implementations also show a drop in understanding with substantial or low effect sizes (as d is in between -0.09 to -0.026), however, none of the drops are statistically significant ($p > 0.1$).

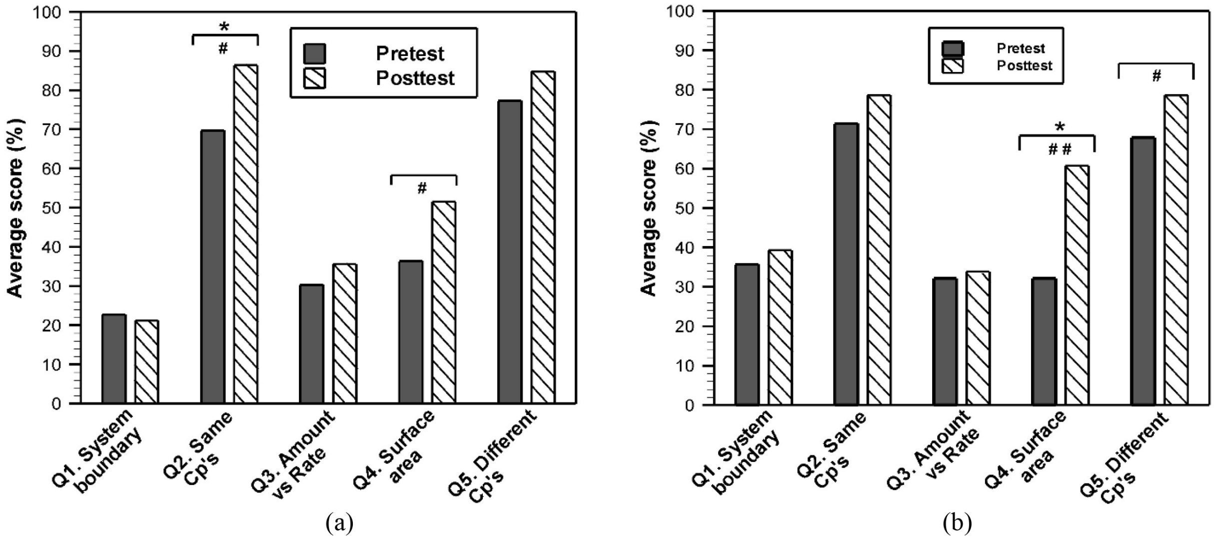
Except for one implementation (WSU-S17), in Question 3, students were asked to choose the correct pressure vs axial location graph in a suddenly expanded and then suddenly contracted pipe. Statistics of Question 3 show an increase in the posttest score for five implementations and a non-significant decrease in one implementation ($p = 0.333$ and $d = -0.27$) (Fig. 3c). Among the improved cases, two show significant improvements with at least at the 95% confidence level ($0.01 < p \leq 0.05$) and low to moderate effect sizes ($d = 0.38$ and 0.45). In the WSU-S17 demonstration, the third question was replaced by a new question in which students were asked to select the physical meaning of Bernoulli's equation (see Appendix A). The assessment shows a significant improvement in understanding with a confidence level higher than 99% ($p < 0.001$) and high effect size ($d = 0.77$).

4.2 DLMs for Heat Transfer

We have developed and implemented two DLMs: double pipe and shell & tube heat exchanger modules to address misconceptions about heat transfer-related concepts. The double pipe heat exchanger was implemented in the chemical engineering department of the UI, Moscow, and in the mechanical engineering department of the WSU, Pullman. The shell & tube heat exchanger was implemented in the mechanical engineering department at UCO, Edmond and in the chemical engineering department at WSU, Pullman. The results of these implementations are shown in the following sections.

4.2.1 Double Pipe Heat Exchanger Module

The pre- and posttest assessment results for the



(a) (b)

Fig. 4. Double pipe heat exchanger module implementations result from (a) WSU-S17 and (b) UI-S17. Number of data points are $N = 66$ for WSU-S17, $N = 29$ for UI-S17. * and ** indicate significance at the 95% and 99% confidence levels, respectively. #, ## and ### indicate small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$) and large ($d \geq 0.8$) effect sizes, respectively.

double pipe heat exchanger DLM implementation are shown in Fig. 4 with statistical results summarized in Table 4. Since the total number of double pipe heat exchanger implementations was comparatively low, the results are presented based on implementation location rather than individual questions.

In the first question (Q1, Fig. 4), students were asked to select/draw system boundaries to determine the amount of heat transferred from the hot to the cold fluid. The resulting data shows no statistically significant change in conceptual understanding from the pre- to posttest. Surprisingly, at WSU and UI only ~20% and ~35%, respectively, answered this question correctly both before and after DLM implementation. In Question 2, students were asked to select which fluid will have the largest temperature change when both fluids are water, but hot fluid has a double mass flow rate than cold fluid. Although students had a good understanding (high pretest score) of this question before the implementation, still there is improvement in understanding after implementation of DLMs. For example, in the worst-case scenario (Fig. 4b, Q2), there is an ~8% increase in the average score while, in the best case (Fig. 4a, Q2), there is ~15% increase. Therefore, among two implementations, one implementation shows significant improvement with more than a 95% confidence level ($p = 0.027$) and low effect size ($d = 0.42$). In Question 3, students were asked to compare two ice melting options differentiating between heat transfer rate and amount. The results show that, in both implementations, both pre- and posttest scores are below 40% with non-significant improvement ($p > 0.05$) and negligible effect sizes ($d < 0.2$) (Q3, Fig. 4 and

Table 4. Statistics on double pipe heat exchanger modules

Question	Implementation site	Mean ± Std. Error		P-value, *p*	Effect Size, *d*
		Pretest	Posttest		
Q1. System boundary	WSU-S17	2.27 ± 4.22	2.12 ± 4.12	0.742	–0.04
	UI-S17	3.57 ± 4.79	3.93 ± 4.88	0.736	0.07
Q2. Same Cp's	WSU-S17	6.97 ± 4.63	8.64 ± 3.46	0.027*	$0.42^{\#}$
	UI-S17	7.14 ± 4.52	7.86 ± 4.10	0.474	0.16
Q3. Amount vs rate	WSU-S17	3.03 ± 4.37	3.56 ± 4.62	0.300	0.12
	UI-S17	3.21 ± 4.06	3.39 ± 4.24	0.807	0.04
Q4. Surface area	WSU-S17	3.64 ± 4.85	5.15 ± 5.04	0.067	$0.31^{\#}$
	UI-S17	3.21 ± 4.67	6.07 ± 4.88	0.014*	$0.60^{\#\#}$
Q5. Different Cp's	WSU-S17	7.73 ± 4.22	8.49 ± 3.61	0.228	0.19
	UI-S17	6.79 ± 4.67	7.86 ± 4.10	0.309	$0.25^{\#}$

* and ** indicate significance at the 95% and 99% confidence levels, respectively. #, ## and ### indicate small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$) and large ($d \geq 0.8$) effect sizes, respectively.

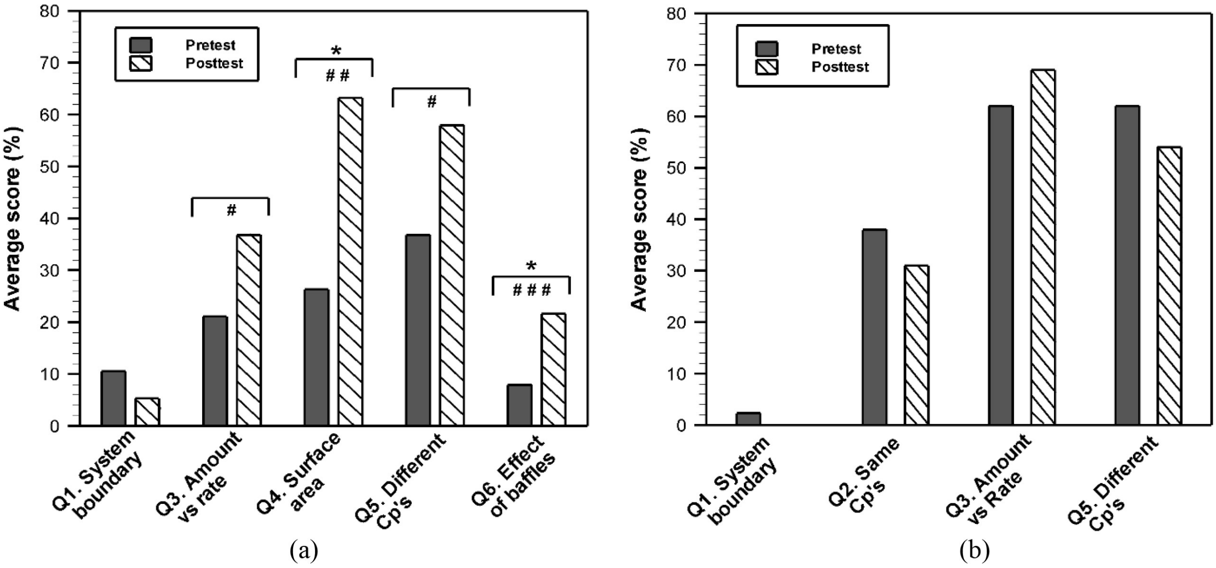


Fig. 5. Shell and tube heat exchanger module implementations (a) UCO-F16 and (b) WSU-S18. The number of data points is $N = 19$ for UCO-F16, $N = 26$ for WSU-S18. * and ** indicate significance at the 95% and 99% confidence levels, respectively. #, ## and ### indicate small ($0.2 \leq d < 0.5$), medium ($0.5 \leq d < 0.8$) and large ($d \geq 0.8$) effect sizes, respectively.

Table 4). In Question 4, students were asked to select the correct expression for the heat transfer surface area, A_o used in $\dot{Q} = U_o A_o \Delta T_{LMTD}$. The assessment showed that there is an improvement in student conceptual understanding of the topic from pre-test to posttest at both universities with low to moderate effect sizes (d = 0.31 and 0.60) with statistically significant improvement with 90% and 95% confidence levels at the WSU and UI (p = 0.067 and 0.014), respectively. Again, the energy balance concept had been tested in Question 5. In this question, students were asked to select which fluid will have the largest temperature change when both fluids have the same mass flow rate, but hot fluid is air and cold fluid is water. As seen in Fig. 4 (Q5), more than 70% of students answered this question correctly before the implementation, but still, there is improvement in understanding as shown by ~8% higher score in posttest in both implementations. However, these improvements are not statistically significant (p > 0.05), and the effect sizes are also small (d = 0.19 and 0.25).

4.2.2 Shell & Tube Heat Exchanger Module

Fig. 5 shows the pretest and posttest assessment results of shell & tube heat exchanger DLM implementations at UCO (Fig. 5a) and WSU (Fig. 5b). Due to similarities between the double pipe and shell & tube heat exchangers, similar concepts such as system boundaries, energy balance, heat transfer area, etc. are also tested during shell & tube heat exchanger implementations.

The overall student understanding of Question 1 regarding system boundaries is very low both before and after implementation. Less than 10% of students answered correctly on the pre-test at UCO and WSU, and scores on the posttest showed no significant change (p > 0.05), with less than 6% at UCO and none at WSU answering correctly. The effect size at UCO is small (d = 0.19) but the effect size at WSU is undetermined because of no correct answer in the posttest. In Question 2, students (only at WSU) were asked to select which fluid will have the largest temperature change when hot water has a double mass flow rate than cold water. Assessment showed that there is a non-significant (p > 0.05) decrease in score from pre-test to posttest with negligible effect size (d = –0.15) (Q2, Fig. 5b). The differences between heat content and heat transfer rate were addressed in Question 3 of both implementations. An improvement is observed in the average score from pre-test to posttest (Q3, Fig. 5) in both implementations: from 21.1% to 36.8% at UCO (Q3, Fig. 5a) and from 62.0% to 69.0% at WSU (Q3, Fig. 5b), respectively. However, none of these are statistically significant (p > 0.05) and effect sizes are low (d = 0.35 and 0.15 at UCO and WSU, respectively). The surface area for heat transfer in the case of shell & tube heat exchanger was tested in Question 4 only for UCO implementation. A significant (p = 0.049) improvement in understanding level has been observed for this question with large effect size (d = 0.78). The effect of heat capacity of fluid on its physical temperature was tested in Question 5. At UCO (Q5, Fig 5a), the understanding level is increased by 21%; while, at WSU (Q5, Fig. 5b), the understanding level is decreased by 8% after the DLM experiment. Although none of these are statistically significant (p > 0.05), the effect sizes are low (d = 0.47) and negligible (d = –0.16) for

Table 5. Statistics on shell & tube heat exchanger module

Question	Implementation site	Mean ± Std. Error		P-value, *p*	Effect Size, *d*
		Pre-test	**Post-test**		
Q1. System boundary	UCO-F16	1.05 ± 3.15	0.53 ± 2.29	0.578	–0.19
	WSU-F18	0.23 ± 0.82	0.00 ± 0.00	0.161	NA^{+}
Q2. Same Cp's	WSU-S18	3.80 ± 4.96	3.10 ± 4.71	0.574	–0.15
Q3. Amount vs Rate	UCO-F16	2.11 ± 4.19	3.68 ± 4.96	0.268	0.35$^{\#}$
	WSU-F18	6.20 ± 4.96	6.90 ± 4.71	0.574	0.15
Q5. Different Cp's	UCO-F16	3.68 ± 3.94	5.79 ± 5.07	0.237	0.47$^{\#}$
	WSU-F18	6.20 ± 4.96	5.40 ± 5.08	0.627	–0.16
Q4. Heat transfer area	UCO-F16	2.63 ± 4.52	6.32 ± 4.96	0.049*	0.78$^{\#\#}$
Q6. Effect of baffles	UCO-F16	0.79 ± 0.92	2.16 ± 2.52	0.050*	0.90$^{\#\#\#}$

* and ** indicate significance at the 95% and 99% confidence levels, respectively. #, ## and ### indicate small $(0.2 \le d < 0.5)$, medium $(0.5 \le d < 0.8)$ and large $(d \ge 0.8)$ effect sizes, respectively. $^{+}$For this case, calculation of effect size was not possible because the posttest score was zero.

Table 6. Faculty survey results

Question category	Question descriptions	Response (N=7)
1. Facilitating student learning	DLM's ease of use helps with the understanding of course concepts.	66.7% strongly agree, 33.3% agree$^{\pm}$
	DLM's ease of use makes working through the worksheets straightforward.	42.9% strongly agree, 42.9% agree, 14.3% neutral
	DLMs are suitable for meeting a host of student learning styles, e.g., visual, interactive, hands-on, etc.	71.4% strongly agree, 14.3% agree, 14.3% strongly disagree
	A worksheet guided Desktop Learning Module (DLM) is advantageous over students merely working with the hands-on units by themselves with no guidance.	100% strongly agree
2. Ease of use	Flexibility in how a faculty member decides to use the DLMs, e.g., in the classroom, lab, or as a take-home unit makes the system adaptable to a philosophy of teaching.	71.4% strongly agree, 14.3% agree, 14.3% neutral
	The DLM offers flexibility in activity selection so that I can focus on the concepts I wish to cover.	28.6% strongly agree, 42.9% agree, 28.6% neutral
	The complexity of the DLMs and their use makes it difficult for students to focus on specific concepts.	28.6% strongly disagree, 42.9% disagree, 14.3% agree, 14.3% strongly agree
	The challenges of getting all the parts together for the DLMs make their use impractical.	42.9% neutral, 28.6% disagree, 28.6% strongly disagree
	Having a video tutorial would help guide the DLM setup and use.	71.4% strongly agree, 28.6% agree
3. Support and infrastructure	There are philosophical barriers in the way we approach our curriculum that make DLM implementation difficult.	28.6% strongly disagree, 57.1% disagree, 14.3% neutral
	I have support for use of novel teaching practices such as using hands-on DLMs from my administrators.	71.4% strongly agree, 28.6% agree
	Budget constraints make the procurement of DLMs for classroom use a barrier.	57.1% agree, 28.6% neutral, 14.3% strongly disagree
	There are logistical challenges in transferring DLM implementation to our university.	42.9% strongly disagree, 57.1% disagree

$^{\pm}$ One faculty member provided no response to this question, therefore N = 6 for this question only.

UCO and WSU, respectively. In Question 6 for UCO, students were asked to explain the effect of increasing the number of baffles at a constant flow rate, on the heat transfer rate. As shown in Fig. 5a (Q6), there is a significant improvement ($p = 0.05$) in understanding level with high effect size ($d = 0.90$). The overall statistical results for shell & tube heat exchanger implementations are summarized in Table 5.

4.3 Faculty Survey

In addition to the impact of DLM use on conceptual understanding, the disseminability or adoption of DLMs was assessed by carrying out a 13 questions survey about features of the DLMs such as ease of use, and support and infrastructure, in facilitating student learning. In this survey, each question was asked using a Likert scale with five answer choices: strongly agree, agree, neutral, disagree, and strongly disagree. The survey was completed by seven faculty who implemented DLMs in their courses (not including project PIs). The results of that survey for individual questions are summarized in Table 6 where the vast majority of surveyed faculty members responded in favor of the adoption of DLM pedagogy. For example, for the first category of questions, 70.3%, 22.6%, 3.6%, 0.0%, and 3.6% of faculty members strongly agree, agree, neutral, disagree, and strongly disagree, respectively, that these DLMs facilitate student learning. In addition, for the second category of questions, 45.7%, 31.5%, 17.2%, 2.9%, and 2.9% of faculty members strongly agree, agree, neutral, disagree, and strongly disagree, respectively, that these DLMs are very easy to use in the classroom. Moreover, 39.3%, 35.7%, 10.7%, 14.3, and 0.0% of faculty members strongly agree, agree, neutral, disagree, and strongly disagree, respectively, that their universities have logistic support and infrastructure to implement DLM.

5. Discussion

5.1 DLMs for Fluid Dynamics

5.1.1 Hydraulic Loss Module

For use of the hydraulic loss DLM, three questions were asked in the pre- and posttest to determine the efficacy in terms of improving conceptual understanding across beta site implementations. In some cases, questions that relate less directly to DLM activities showed reduced conceptual understanding, as one might expect. This was the case for Question 1 on the hydraulic loss pre-/posttest, where students were asked to select the correct pressure vs. axial location profile in a suddenly expanded and contracted pipe (Fig. 2a). Moreover, this questions falls under the analyze category in Bloom's taxonomy because students need to use information in new situations. Answering this question correctly requires knowledge about both frictional head loss, i.e. hydraulic loss, as well as energy transitions between kinetic and flow work. While the frictional head loss component is learned through hydraulic loss experiments, students would have to solely rely on the lecture to incorporate knowledge of energy transitions other than frictional losses. As there is no change in diameter within the system, students were unable to deduce energy transitions experimentally. Therefore, it is not surprising that there no statistical improvements for this question except at one implementation at UK-Pad-F18). From this, we can conclude that if answering a question requires knowledge that is not directly depicted by DLM implementation, an accurate assessment of student learning with DLMs is not guaranteed. We next go to questions where there is a stronger tie to the principles embodied in the DLM exercises.

As anticipated, for a question more directly related to the DLM activity there is strong evidence for improvement across institutions. For example, Question 2, selection of the correct velocity vs axial location plot for flow through a pipe, is related to the DLM activity, therefore, it shows significant improvement in conceptual understanding. This question falls into apply and analyze categories in Bloom's taxonomy because this requires the application of concepts learned with the DLM to a slightly different scenario, flow between two reservoirs, rather than simple pump-driven recirculation through a tube with standpipes for measuring pressures. As a result of the use of the DLM, students are demonstrating their understanding at higher Bloom's levels of applying and analyzing as they transfer understanding gained in the DLM exercise to the new context, and thus step improvements are occurring everywhere the DLMs are implemented.

Surprisingly, the transference of understanding of pressure vs axial location (Question 3) to the new scenario does not occur uniformly. The reason for the disconnect is uncertain, but we hypothesize that students may incorrectly think the system behaves more like a static system where liquid pressure heads are equal at any point for a pipe extending from a tank. To clarify what is happening in the posttest question, we are removing the second reservoir and may add a streamlined flow of liquid or an arrow exiting to the surrounding air and will gather corresponding results over future implementations to assess if this makes any difference in the results.

5.1.2 Venturi Module

Associated with the venturi DLM implementation, three questions were asked in the pre- and posttest to further verify efficacy in terms of improving conceptual understanding of fluid mechanics concepts. In Question 1, students were asked to select the most realistic representation of the pressure vs axial location in a venturi meter. Although this question originally falls into the analyze category in Bloom's taxonomy, the see-through nature of this DLM converts this into a lower Bloom's level question and helps students to understand the energy transition concepts. Therefore, it is not surprising that students perform far better on the posttest for these types of questions. Since there is a chance that students may simply remember the distribution of what they have seen during the venturi DLM experiment, we asked the students to briefly explain their reasoning for the selection. It was found that student explanations in the posttest became more reasonable, appropriate, and closer to the actual explanation of the physical phenomenon. For example, a student's pretest reasoning for this question was "At point (A), velocity and pressure (let's assume they are the same); at (B), the velocity increases causing a pressure drop; hence, pressure decreases when velocity increases; at point (C), the velocity and pressure will be the same as point (A)". On the posttest, the student was able to provide a more accurate and significantly more detailed description of the pressure profile, stating, "The pressure will drop from point A to point B and as the fluid reaches point C the pressure will be somewhat less than at point A; as the area is reduced velocity must increase to maintain flowrate; in the venturi meter, some of the energy is lost to friction; the Bernoulli equation relies on inviscid flow, which means that the energy lost due to viscosity is negligible. I think that in an ideal case that choice f is the right answer, but if this is the most realistic case, I think some pressure is lost, which is why I chose option e." As evident from this student response, the reasoning is changed from the pretest response assumption that frictional losses are negligible to the more realistic posttest understanding that frictional losses cannot be recovered in this system.

Once again, when concepts are not directly visible during DLM experimentation, the understanding of questions that comes from a higher Bloom's level (analyze or above) becomes cumbersome. As a result, statistics of velocity distribution in venturi (Question 2) show ambiguous results from one implementation to another. As stated earlier, the pressure distribution is visualized during DLM experimentation due to the transparency of the manometers, however, visual demonstration of the velocity distribution is not feasible with the venturi DLM. Therefore, students have to use the Bernoulli equation to convert their pressure distribution knowledge to understand velocity distribution. But, during the conversion, some students did not consider the frictional loss in the Bernoulli equation and this may be a cause for ambiguous results. To address this in future implementations, small beads will be used to enhance the visualization of fluid velocity along the axial direction of the venturi. The flow of the beads in the venturi will demonstrate that fluid velocity increases nonlinearly at the throat, allowing students to better answer this question through visual understanding.

Except for one implementation (WSU-S17), in Question 3, students were asked to choose the correct pressure vs axial location profile in a suddenly expanded and then suddenly contracted pipe (the same as Question 1 of the hydraulic loss module). As stated earlier, this is an analyze level question in Bloom's taxonomy and the underlying physical phenomenon was not addressed through the hydraulic loss experiment. However, we hoped that the venturi DLM could provide an excellent understanding of energy transitions and frictional head loss concepts during fluid flow through a non-uniform diameter pipe. Results are favorable as statistics for this question show an increase in assessment scores for five out of six implementations after DLM implementation. In comparison to the results obtained for the same question used in the hydraulic loss DLM assessment (Fig. 2a), venturi data (Fig. 3c) show significantly more favorable results. From the venturi DLM, students acquired energy transition as well as frictional loss knowledge, and thus, they were able to transfer that knowledge to a new opposite scenario i.e. pressure distribution in a pipe with sudden enlargement in diameter. This indicates that the venturi is more suitable than the hydraulic loss DLM for understanding the pressure distribution in a suddenly enlarged section and is further evidence that students can more easily understand key concepts when they can visualize the phenomena.

5.2 DLMs for Heat Transfer

5.2.1 Double Pipe Heat Exchanger Module

As discussed for the fluid mechanics DLMs, we again consider the impact of physical attributes on improvements in understanding. The identification of the system boundary (Question 1) for an energy balance requires understanding of the system concept, using information in a new situation and drawing connections among ideas. These requirements force this question into the analyze level in Bloom's taxonomy. The low numbers, in the 20–35% for correct scores for both pre- and posttests tell us that an understanding of the system boundary is not easily deduced from direct visualization of the DLM especially when students are given a schematic diagram. Although DLMs provide necessary knowledge about where heat transfer occurs and how to calculate it, students could not feasibly deduce how to select an appropriate system boundary for analyzing the amount of heat transfer solely from DLM experiments. In theory, system boundaries need to be chosen such that the necessary information to calculate heat transfer rates, i.e., temperatures, mass flow rate, etc., are known at the boundaries. In future work, we can provide the energy balance equation, $\dot{Q} = \dot{m}C_p(T_{out} - T_{in})$ for a given stream and ask students to locate on the DLM itself the points at which they would find the inlet and outlet temperatures, and metal surface boundary through which heat is transferred from a warmer to a cooler flowing liquid, and hope that this will give more desirable outcomes.

In Questions 2 and 5 (Q2 and Q5, Fig. 4), students were asked to select which fluid will have the largest temperature change and justify the answer when heat transfer occurs from a hot fluid to a cold fluid. This question belongs to the apply level in Bloom's taxonomy as students need to execute an energy balance to answer the question. Here we see improvements, though they are not dramatic. Certainly, this is partly due to the very high pretest score for these two questions. A very high pretest score indicates that most of the students had a priori understanding of the concept of heat capacity coupled with an energy balance from prior mass and energy balance, transport, and/or thermodynamics classes typical in chemical/mechanical engineering curricula. Nevertheless, even with high pretest scores, further improvements occur across institutions. We attribute this to the fact that with color-coded hot and cold fluids, students have a template of mental image of two fluids exchanging heat with one another. Then all they need to do is conceptually superimpose an energy balance upon this image for each stream. When they think about lower heat capacity for one fluid relative to another, it is not a big deal to think that when heat is transferred a larger temperature change will occur for a fluid having lower heat capacity. This idea of stored visual imagery was highlighted in previous publications [8] that when a quantity of heat has transferred from one fluid to another, the temperature difference between two fluids will be compensated. This is another example of the positive results that are seen in highly visual concepts with the aid of DLM exercises.

Question 3 (Q3, Fig. 4) is an evaluate level question in Bloom's taxonomy as students need to compare two systems based on heat energy content and make a decision. This is a rate vs. amount question where one has to compare total heat transferred after equilibrium is reached, for a metal block at 200°C to that for two metal blocks at 100°C. Conceptually this relates to Questions 2 and 5, but in this case, there is no mental images created by a commensurate DLM. Therefore, implementation of the DLMs does not integrate the working memory information with long term memory information and because of that students fail to calculate the amount of ice melted for each scenario. We hypothesize that students were confused by the differences in the dynamic and static situations. This guide to the need for a separate DLM to further enhance understanding of amount in contrast to the rate of heat transfer.

As was previously demonstrated for the fluid dynamics implementations, when a parameter/quantity is directly observable by the DLM experiments, there is a well-defined student learning outcome. In Question 4, students were asked to select the correct expression to calculate heat transfer surface area, A_o in $\dot{Q} = U_o A_o \Delta T_{LMTD}$. Since the see-through design of DLM offers direct observance of the heat transfer surface area, students were able to identify the correct response. As a result, there is an improvement in student conceptual understanding pre- to posttest.

5.2.2 *Shell and Tube Heat Exchanger Module*

Similar to results for the double pipe heat exchanger, shell and tube results show a lack of understanding of the system boundary needed to establish heat transfer rates, with all scores below 10% and understanding level of this concept further deteriorating markedly after the implementation. We hypothesize that the reason is due to the structure of the shell & tube heat exchanger being much more complex than the double pipe. It is easier for the students to just select a system as the entire content of the shell & tube system so they don't miss any streams. We found that approximately 2/3 of the total students selected the entire content of the shell & tube system. Since the system boundary is not a concept understood by visualization, the more complex design of the DLM likely confused the students further.

As seen with the shell and tube implementations, students at UCO have a good understanding of energy balance concepts (Fig. 5, Q5) after the implementation of DLMs. However, in the case of WSU, conceptual understanding decreases, though not significantly, after the DLM experiment (Q2 and Q5, Fig. 5b). Why WSU students' data did not show improvement here is uncertain and further studies are needed to see if the same issues are noted.

The misconception between the amount of heat transferred and the heat transfer rate before and after the shell & tube heat exchanger module was assessed at UCO and WSU. Again pretest scores are low for UCO and an improvement with a small effect size has been observed. In the case of WSU, pretest scores are high and a small improvement in score is observed. Perhaps the small improvement is a result of a testing effect as students reflect or even discuss the answer between the double pipe and shell & tube implementations. Again, a non-steady state batch process is postulated to be of importance for future studies.

Similar to the double pipe heat exchanger data, there is a significant improvement in understanding of surface area concepts, A_o in $\dot{Q} = U_o A_o \Delta T_{LMTD}$ (Q4, Fig. 5a). This indicates that the see-through nature of the DLM cartridge helps students to easily grasp the concept of surface area for heat exchange and, in this case, despite the more complex structure of the shell & tube heat exchanger.

The only question which is truly specific to the shell & tube heat exchanger is Question 6. This question also belongs to the evaluate category in Bloom's taxonomy since students need to critically judge what happens to the heat transfer rate if the number of baffles is increased and a constant shell-side feed flow rate is maintained. Although this is not an effect that can be directly visualized within the DLM experiment, implementation of DLMs and associated activities reinforce student imagination and improves knowledge integration. As a result, significant improvement in understanding takes place after the DLM implementation. We postulate that an even greater increase is likely, if students were asked to compare two shell & tubes systems side-by-side operating at the different flow rates and wrestle with what happens to superficial velocity due to the reduced cross-section for flow and its influence on the Reynolds number, turbulence and thereby the heat transfer coefficient.

5.3 Overall Learning Improvement

Fluid mechanics and heat transfer always offer higher level Bloom's taxonomy questions. In general, problems at the higher Bloom's levels offer high element interactivity with higher cognitive load. But CLT suggests that learning occurs better if interactivity between elements is low and the total amount of cognitive load is lower than the limit of individuals' working memory [38]. Therefore, by deviating from the conventional classroom setting, the use of DLMs provide a better understanding of complex transport problems at higher Bloom's levels. In the current context, the use of DLMs allows visualization of element interactivity which helps to manage cognitive load for the complex subject matter at hand. Moreover, the use of DLMs provokes the utilization of schemas. For example, students did better after the DLM activity on the last question for the shell and tube heat exchanger even though the concept was not directly observable through use of the DLMs. In that question, students were asked to predict heat transfer rate if the number of baffles were increased. During the implementation of the shell and tube heat exchanger, students visualized the function of baffles because of the see-through nature of DLMs. Later, when students encountered the question related to baffles, they quickly surmised by using their prior knowledge that fluid velocity will increase because of the larger number of baffles. Therefore, dealing with a heat transfer correlation within their working memory, they quickly realize that the heat transfer coefficient increases because of higher fluid velocity. Thus, at any particular time, the working memory is not dealing with too many elements which serves to lower the cognitive load. Moreover, with hands-on DLMs, students have the opportunity to recall existing knowledge (active), construct new knowledge or improve upon existing knowledge (constructive), and interact with peers to build upon understanding (interactive). Thus, implementation of DLMs engages students in all three active modes of learning. For example, during the implementation, each student tried to understand the energy balance principle by drawing his/her own schematic of a heat exchanger and then discussing it with one another in a group. Therefore, an interactive mode of engagement occurred during the learning process through DLMs experimentation. According to the ICAP hypothesis that would lead to better overall learning outcomes.

5.4 Faculty Survey about Adoption of the DLMs

Although the need for improvement in STEM educational materials and curriculum is well acknowledged, the dissemination and adoption of new pedagogies remain a significant challenge. A previous study by Hazen et al. [3] employing over 20 subject-matter experts suggested that there are several important factors to consider when attempting to facilitate the adoption of new educational tools for engineering courses. Specifically, they show that the new educational tools must demonstrate a clear advantage over existing materials, are synergistic with and/or adaptable to existing curricula, are not overly complex, and are, overall, easy to utilize [3]. Lee et al. [39] discussed the different variables that can promote or inhibit the adoption of new educational materials. Some of the factors that are said to promote adoption are compatibility – consistency with current tools or the ability to use new approaches synergistically [19], management support – the level of support provided by institutional authorities for adoption of new pedagogies [40], usability – the effectiveness of the new tool in facilitating education [41], enhancement of visibility – the ability to observe/visualize the new tool [19], and playfulness – the amount of interaction between the educational tool and the students [42]. The factors that are said to inhibit the adoption of new educational pedagogies are complexity – the difficulty of use of the new tool [19], and anxiety in use – concerns associated with utilization of the new tool [43].

As stated in the results section under faculty survey regarding DLM usage and implementation in engineering courses indicate that educators are strongly in favor of DLM use in the classroom which we broadly categorize as facilitating student learning, ease of use, and a supportive environment and infrastructure. These basic attributes can more finely be aligned with the factors just outlined for facilitating the implementation of new learning approaches. Potentially one of the most important factors in the adoption of new pedagogies is demonstrated evidence that the new technology is effective in teaching the desired curricula. While the student conceptual data presented above demonstrated that DLMs are effective educational tools especially for concepts with a visual component, further evidence was provided in the faculty survey where 100% of responders felt that DLMs are effective in aiding in student understanding of course concepts. Another significant concern in the adoption of new pedagogy is compatibility with existing curricula. Our faculty survey results (Table 6) demonstrate that 71.4% of responders strongly agree that DLMs are flexible and adaptable to a variety of teaching philosophies with none of the responders stating that DLMs are too difficult to incorporate into their teaching style. Further, 71.4% of respondents agreed or strongly agreed that DLMs provide the flexibility to tailor activities to cover the topics of the instructors, while none of the responders stating that they could not cover topics of their choosing with DLMs and associated pedagogy.

Additionally, due to the highly visual and tactile nature of this new tool, 85.7% of responders indicated that DLMs are effective in education in a variety of learning styles. While the definition of styles was not given in the survey, many are familiar with abundant literature spearheaded by Felder [5] on the wide variety of learning styles which include sensory/intuitive, visual/auditory, inductive/deductive, active/reflective, and global/sequential. The implementation of DLMs in the classroom allows room for incorporating these learning styles. For example, the see-through nature of DLMs highly quickens the visual learning style; while student participation through doing DLM experiments agitate the active/reflective learning style. Finally, the support for the adoption of the new pedagogy by institutional leaders is also considered a pivotal concern where instructors require the support of university or department leaders to be able to adopt new methods in their courses. The faculty survey demonstrates that faculty members responded positively to the use of LC-DLM cartridges in their classroom with the majority agreeing that the modules are easy-to-use, are facilitating student learning, and offer students a valuable tool to understand core heat transfer and fluid mechanics concepts, are adaptable to a variety of uses inside/outside the traditional classroom, and are supported by their university. This is a strong indication of the potential for widespread acceptance of new and effective educational practices due to the need for novel changes in STEM and specifically engineering curricula. The primary factor that is thought to inhibit the adoption of pedagogy is the complexity associated with the setup of the new educational tool. However, according to the conducted faculty survey, more than 70% of respondents felt that DLMs and associated experiments are not overly complex and do not impede students' ability to focus on the intended learning objectives. Overall, results from the faculty survey of DLMs implementers demonstrate exceptional potential for dissemination and adaptability due to their effectiveness in enhancing learning, adaptability for use in varied classroom setups, see-through nature, and ease of use.

5.5 *Recommendations for Future Studies*

While improvements in conceptual understanding are significant in specific instances with DLMs and faculty satisfaction is high, instances of variation are observed from one implementation to the next. For example, in the case of shell & tube heat exchangers, implementation at WSU exhibits unfavorable results while implementation at UCO shows very favorable results. A more comprehensive study is needed to understand why these variations in student performance are observed. Such data will be forthcoming over the next two years as currently a 5-year study of DLM implementations and student performance is underway involving approximately 50 institutions nationwide. In those comprehensive studies, instructors will be requested to provide detailed information regarding the methods of instruction associated with DLM implementation in their courses. Of particular interest in this type of data is the procedure of implementation to discern whether the DLM activities are combined with the lecture or if the students are expected to build associated conceptual understanding based on the DLM activity alone. We hypothesize that higher learning gains are associated with more coverage of relevant material and that lectures combined with DLMs likely result in higher gains than lecture or DLM use alone. Other aspects of implementation include the time proximity after which the posttests are given for the DLM activity or whether any material was covered in the lecture before a pretest. Academic standing, whether students are sophomores or juniors during which they take the courses associated with DLMs may also be an important factor. How much of the DLM activity students were able to complete within the classroom setting, how the DLM activity was performed, and the number of students in the course and each implementation group may all be factors. Hence, we expect the ongoing more comprehensive study will be pivotal in fully understanding disparities in student data and the full impact of DLM usage on student learning.

6. Conclusions

Low-cost DLMs were developed to aid student learning of key fluid mechanics and heat transfer concepts. These DLMs, namely hydraulic loss, venturi meter, double pipe and shell & tube heat exchanger modules are shown to be effective in teaching key concepts in classroom settings. While preliminary work has shown strong evidence of improvements in learning gains due to DLM usage, widespread dissemination and adoption of new pedagogy require the proven ability to translate this technology to a wide variety of institutions and settings. Without effective dissemination, the positive impacts of DLMs cannot be shared with students and instructors nationwide. This technology has the potential to immensely impact student learning in STEM education and widespread propagation will be extremely impactful for students and instructors alike. In this paper, the disseminability of DLMs is supported by data from several implementations in chemical and/ mechanical engineering courses at multiple universities. Overall, the results from the fluid dynamics DLM implementations (hydraulic loss and venturi) showed significantly better conceptual improvements than those from the heat transfer implementations. These results are somewhat expected, however, as the questions asked during fluid dynamics assessments, in general, were more related to concepts that were directly observable during experimentation. Likely, the decreased understanding of heat transfer concepts was due to the more abstract nature of heat transfer concepts. Yet, the collective results of both fluid mechanics and heat transfer module implementations suggest that the modules are vastly effective in physical feature-related concepts such as heat transfer surface area and pressure relationships over less visible features such as velocities within the constructs. Nevertheless, our beta test results indicate that DLMs are effective across curricula despite the differences in educational environments. The various implementation features for use of DLMs were critically evaluated by faculty members indicating that the capacity for facilitating student learning, ease of use in the classroom, and usability with existing support and infrastructure are highly praised by the expert panel. While initial results are promising, a more comprehensive separate study of data from a wider variety of institutions will help parse out whether differences observed from one context to the next are attributable to variations in implementation approaches and academic year in which students take the relevant courses.

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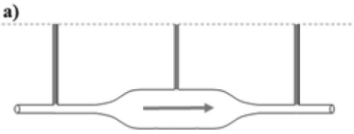
Appendix A: Assessment Questions

A set of pre- and post-test questions were developed that correlate to concepts taught in traditional fluid mechanics and heat transfer courses. For each DLM, the questions can be readily broken down into core concept areas which are listed below along with the full-length questions.

A1: Hydraulic Loss Module

Question 1 Pressure profile in suddenly expanded-contracted pipe: Encircle the figure that most closely represents reality. Note, the standpipes contain liquid exposed to atmospheric pressure at the top, and flow is occurring from left to right.

a)



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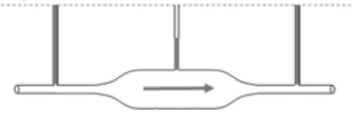
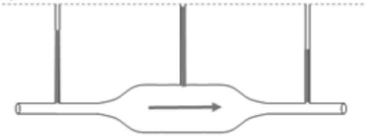


c)



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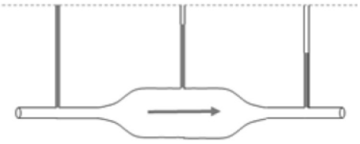
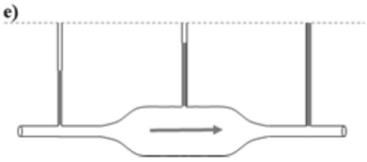


e)



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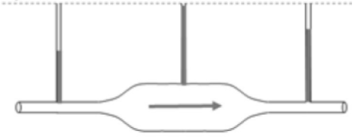
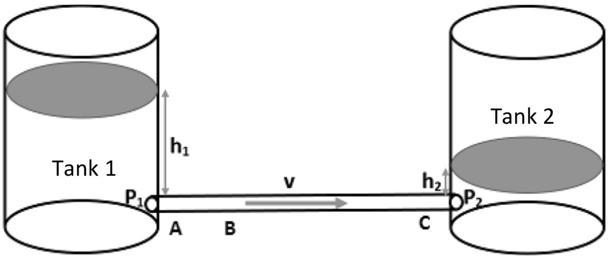
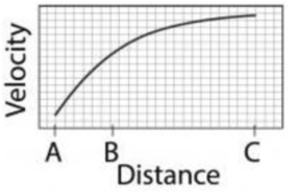


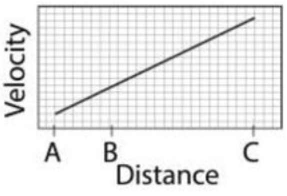
Please answer Questions 2 and 3 based on the following figure.

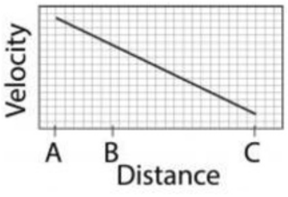


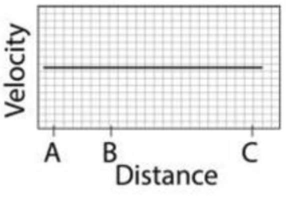
Water flows through the pipe from Tank 1 on the left to Tank 2 on the right. The water level in each tank is indicated at a point in time. At that time, the pressure at the entrance to the pipe from Tank 1 is P_1 = 20 kPa and the pressure at the entrance of Tank 2 is P_2 = 12 kPa.

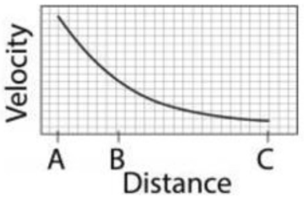
Question 2 (Velocity profile in straight pipe): Select the correct graph of velocity versus distance down the pipe.





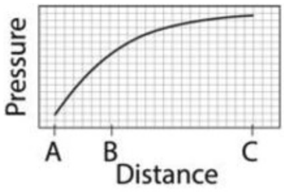


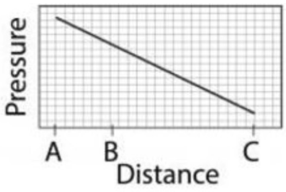


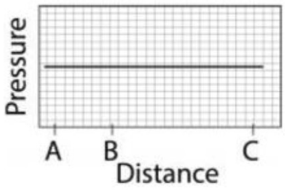


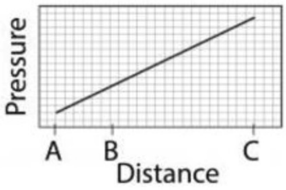
Justify your answer for the velocity vs distance.

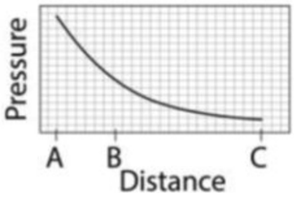
Question 3 (Pressure profile in straight pipe): Select the correct graph of pressure versus distance down the pipe







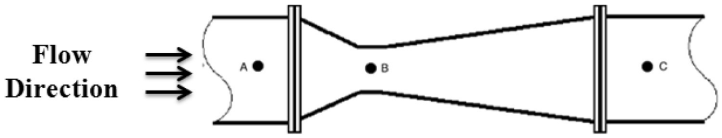




Briefly explain your reasoning.

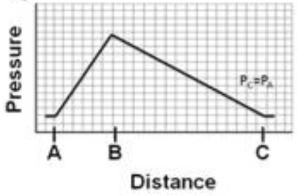
A2: Venturi Module

Please answer Questions 1 and 2 based on the following figure.

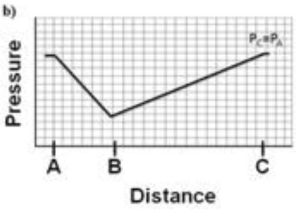


Question 1 (Pressure profile in venturi): Select the most realistic graph for pressure versus length.

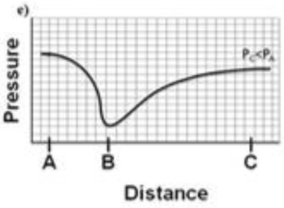
a)



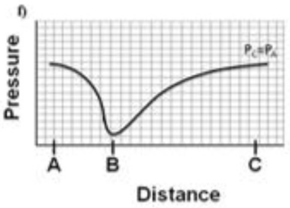
b)



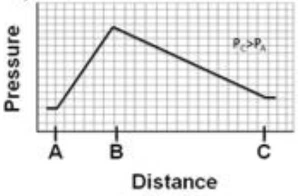
e)



f)



c)



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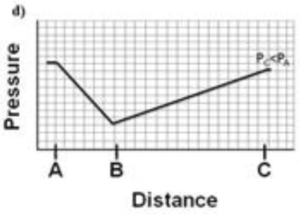
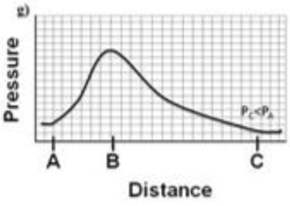
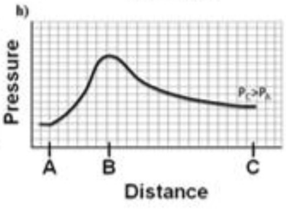


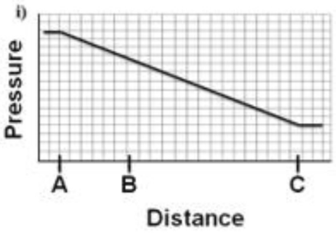
g)



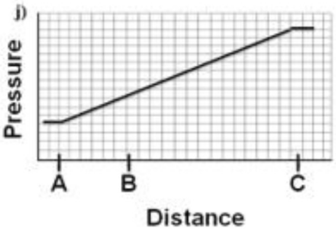
h)



i)



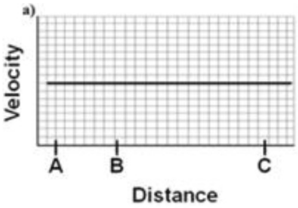
j)



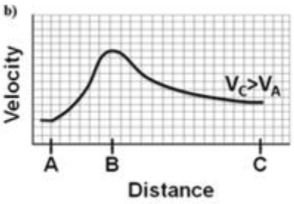
Briefly explain your reasoning.

Question 2 (Velocity profile in venturi): Select the most realistic graph for velocity versus length:

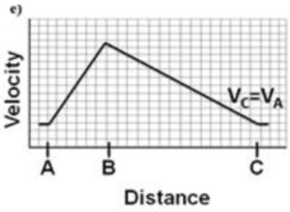
a)



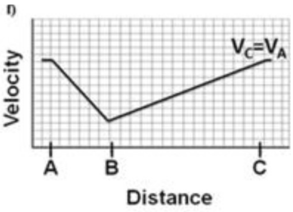
b)



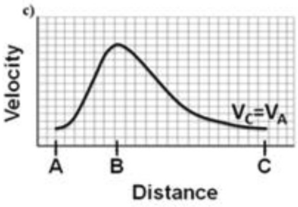
e)



f)



c)



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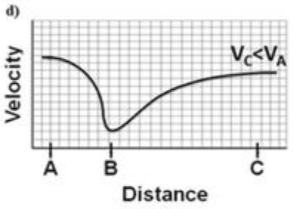
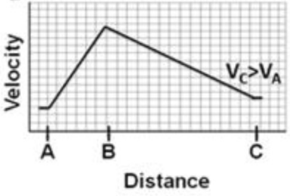
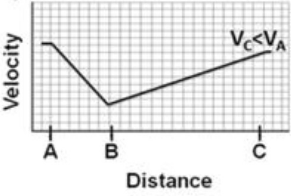


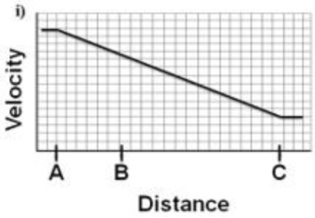
g)



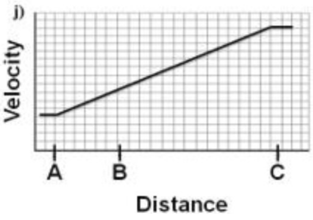
h)



i)



j)



Briefly explain your reasoning.

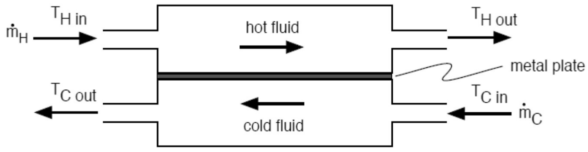
Question 3 (Pressure profile in suddenly expanded-contracted pipe): Same as Question 1 of hydraulic loss module.

Question 4 (Bernouli equation): Bernoulli's equation says along a streamline_____.

(a) Energy is conserved.
(b) Mass is conserved.
(c) Pressure is constant.
(d) Kinetic energy is constant.

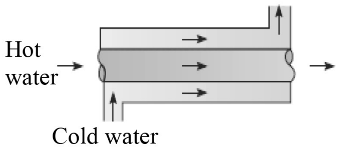
A3: Double Pipe Heat Exchanger

Question 1 (System Boundary): A schematic of a simple heat exchanger is given below. If you want to determine the rate of heat transfer from the hot fluid to the cold fluid, what would you pick as the system to analyze? Please draw the system boundary on the schematic below.



Question 2 (Same Cp's): In a parallel-flow heat exchanger, hot water flows through the inner tubes and cold water flows through the annular side as shown below. If the mass flow rate of the hot water is twice the mass flow rate of cold water, which fluid will experience the largest temperature change?

(a) Hot water.
(b) Cold water.
(c) They both experience the same temperature change.



Explain your answer.

Question 3 (Amount vs Rate): You would like to melt ice which is at 0°C using hot blocks of metal as an energy source. The first option is to use a metal block at a temperature of 200°C and the second option is to use two metal blocks each at a temperature of 100°C. All blocks are made from the same material and have the same mass and surface area. Assume heat capacity is not a function of temperature, if the blocks are placed in identical insulated containers filled with ice water, which option will ultimately melt more ice?

(a) Either option will melt the same amount of ice.
(b) The two 100°C blocks.
(c) The one 200°C block.

Because...

(a) 2 blocks have twice as much surface area as 1 block, so the energy transfer rate will be higher when more blocks are used.
(b) Using a higher temperature block will melt the ice faster because the larger temperature difference will increase the rate of energy transfer.
(c) The amount of energy transferred is proportional to the mass of the blocks and the change in block temperature during the process.
(d) The temperature of the hotter block will decrease faster as energy is transferred to the ice water.

Question 4 (Surface Area): Which area will you use for A_o, in $\dot{Q} = U_o A_o \Delta T_{LMTD}$ in a double tube heat exchanger?

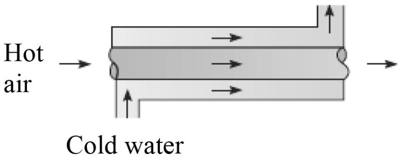
(a) $\frac{\pi D_o^2}{4} N_t$, (b) $\frac{\pi D_h^2}{4} N_t$, (c) $\pi D_o L N_t$, (d) $\pi D_i L N_t$, (e) $\pi D_h L N_t$

We note the students are familiar with the fact that D_h is the hydraulic diameter.

Question 5 (Different Cp's): In a parallel-flow heat exchanger, hot air ($C_p = 1 \frac{kJ}{kg \cdot K}$) flows through the inner tubes and cold water ($C_p = 4.18 \frac{kJ}{kg \cdot K}$) flows through the annular side as shown below. If the mass flow rate of the hot air is the same as the mass flow rate of cold water, which fluid will experience the largest temperature change?

(a) Hot air.
(b) Cold water.
(c) They both experience the same temperature change.

Explain your answer.



A4. Shell & Tube Heat Exchanger
Question 1 (System Boundary): Same as double pipe module question 1.
Question 2 (Same Cp's): Same as double pipe module question 2.
Question 3 (Amount vs Rate): Same as double pipe module question 3.
Question 4 (Surface Area): Same as double pipe module question 4.
Question 5 (Different Cp's): Same as double pipe module question 5.
Question 6 (Effect of Baffles): If we increase the number of baffles and maintain a constant shell-side feed flow rate in a shell & tube heat exchanger what will happen to the heat transfer rate and why?

Aminul Islam Khan received his BS and MS from the Bangladesh University of Engineering and Technology where he also served as a lecturer and an assistant professor. Currently, he is a PhD candidate at Washington State University with multidisciplinary research including hands-on learning for STEM education, drug/particle transport modeling, micro/nanoscale electroosmotic flow investigation, inverse techniques including Bayesian inference, MCMC methods, neural network, and adeno-associated virus and liposome characterization by deep learning. In 2020, he was awarded the best "research assistant award" in the School of Mechanical and Materials Engineering at Washington State University. He plans to pursue a teaching career upon earning his PhD.

Negar Beheshti Pour received her BS degree in Polymer Engineering from Tehran University and her MS and PhD from Washington State University. She then joined UC Berkeley as a lecturer in 2019. Her primary fields of technical research are fluid mechanics of bubbles and the applications of capillary channels for gas-liquid phase separation in microgravity or small-scale systems. Besides her technical research, she has done research in engineering education focusing on improving undergraduate STEM education through in-class hands-on activities. She has been involved in the design and development of ultra-low-cost desktop learning modules (LC-DLMs) using 3D printing and vacuum forming. LC-DLMs allow engineering students to conduct investigations to learn the fundamental principles of fluid mechanics and heat transfer.

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Olusola Adesope is a Boeing Distinguished Professor of STEM Education at Washington State University-Pullman. Dr. Adesope's current research focuses on the use of systematic reviews and meta-analyses for evidence-based practices, cognitive and pedagogical underpinnings of learning with computer-based multimedia resources, and investigation of instructional principles and assessments in STEM education. Dr. Adesope's research is mostly funded by the National Science Foundation and published in top peer-reviewed journals. Dr. Adesope has over 140 published journal papers, book chapters and proceedings and presented over 90 conference papers in national and international conferences. Dr. Adesope is an Associate Editor of the Journal of Educational Psychology and a Senior Associate Editor for the Journal of Engineering Education and sits on the editorial boards of several top-tier journals including the Review of Educational Research, Educational Psychologists, Contemporary Educational Psychology, etc. He is a recipient of several awards including the American Educational Research Association's early career research award.

Bernard J. Van Wie received his BS, MS and PhD, and did his postdoctoral work at the University of Oklahoma where he also taught as a visiting lecturer. He has been on the Washington State University faculty for 39 years and for the past 25 years has focused on innovative pedagogy alongside his technical research in biotechnology. His 2007–2008 Fulbright exchange to Nigeria set the stage for him to receive the Marian Smith Award given annually to the most innovative teacher at Washington State University. In 2016 he was awarded the inaugural Innovation in Teaching Award from the WSI Teaching Academy, the Office of Undergraduate Education, and the Provost's Office for his sustained effort to develop and improve unique instructional tools, namely the "Desktop Learning Modules".

Prashanta Dutta has received his PhD degree in Mechanical Engineering from Texas A&M University in 2001. He started his academic career in the School of Mechanical and Materials Engineering of Washington State University right after his doctoral degree. He was promoted to the rank of Associate and Full Professor in 2007 and 2013, respectively. He served as a Visiting Professor at Konkuk University, Seoul, South Korea (2009–2010) and a Fulbright Faculty Fellow at the Technical University of Darmstadt, Germany (2017). Prof. Dutta is an elected Fellow of the American Society of Mechanical Engineers (ASME). He has authored and co-authored more than 175 peer-reviewed journal and conference papers and delivered more than 75 invited talks all over the world. Currently, he serves as a Deputy Editor for the Electrophoresis.