

Assessing Student Engagement and Conceptual Growth When Using Low-Cost Desktop Fluid Mechanics Learning Modules in Engineering Classes*

GAN JIN

Department of Kinesiology and Educational Psychology, College of Education, Sport, and Human Sciences, Washington State University, PO Box 642114, Pullman, WA, 99164-2114, USA. E-mail: gan.jin@wsu.edu

TALODABIOLORUN ANNE ONI

Voiland College of Engineering and Architecture, Washington State University, Pullman, WA, 99164-2713, USA.
E-mail: talodabiolorun.oni@wsu.edu

FLORENCE OLUWADAMILOLA ADESOPE

Department of Civil & Environmental Engineering, College of Engineering, University of Washington, 201 More Hall, Box 352700 Seattle, WA, 98195-2700, USA. E-mail: adesoflo@uw.edu

BLESSING OPEYEMI AKINROTIMI

Department of Kinesiology and Educational Psychology, College of Education, Sport, and Human Sciences, Washington State University, PO Box 642114, Pullman, WA, 99164-2114, USA. E-mail: blessing.adaramola@wsu.edu

OLUSOLA OLALEKAN ADESOPE

Department of Kinesiology and Educational Psychology, College of Education, Sport, and Human Sciences, Washington State University, PO Box 642114, Pullman, WA, 99164-2114, USA. E-mail: olusola.adesope@wsu.edu

OLUWAFEMI J. AJEIGBE

Texas A&M University, 400 Bizzell St. College Station, TX, 77843, USA. E-mail: oluwafemi.ajeigbe@tamu.edu

OLUWAFEMI JOHNSON SUNDAY

Department of Kinesiology and Educational Psychology, College of Education, Sport, and Human Sciences, Washington State University, PO Box 642114, Pullman, WA, 99164-2114, USA. E-mail: oluwafemi.sunday@wsu.edu

PRASHANTA DUTTA

School of Mechanical and Materials Engineering, Washington State University, Pullman, WA, 99164-2920, USA.
E-mail: prashanta@wsu.edu

BERNARD J. VAN WIE

The Gene and Linda Voiland School of Chemical Engineering and Bioengineering, Washington State University, 1505 Stadium Way, Room 105 P.O. Box 646515, Pullman, WA, 99164-6515, USA. E-mail: bvanwie@wsu.edu

Low-Cost Desktop Learning Modules (LCDLMs) are innovative, affordable educational tools designed to enhance hands-on learning experiences in engineering education. Previous studies have shown the effectiveness of LCDLMs in promoting engineering student engagement and learning outcomes. The present study further explored whether different types of LCDLMs could influence student engagement and learning outcomes differently. This study compared four LCDLMs (i.e., Double Pipe, Hydraulic Loss, Shell & Tube, and Venturi). In total, 2190 undergraduate and graduate students from 29 universities in the United States participated in this study. Results of this study showed that the Shell & Tube module significantly outperformed the Hydraulic Loss and Venturi modules in promoting enhancements in student Active scores. However, no significant differences were observed between the Double Pipe module and the other modules on Active scores. Moreover, the Hydraulic Loss module led to significantly higher knowledge growth compared to the Double Pipe, Shell & Tube, and Venturi modules.

Keywords: low-cost desktop learning modules; engagement; knowledge growth; ICAP

1. Introduction

For the past decade, there has been an increasing interest in understanding how innovative instructional methods could enhance engineering learning in higher education [1, 2]. In engineering education, engagement is a crucial factor that facilitates deeper comprehension [3], whereas a limitation of tradi-

tional instructional methodologies, in which students learn passively, is a lack of motivation and engagement by the students [4, 5].

Low-Cost Desktop Learning Modules (LCDLMs) are aligned with promoting active learning that engages students in complicated engineering learning [6]. Furthermore, previous studies have consistently found that LCDLMs can effec-

tively promote student conceptual understanding and engagement [7, 8]. With the increasing use of LCDLMs in higher education engineering classrooms, we seek to investigate how different types of LCDLMs could influence student learning outcomes and engagement. To be specific, we adopted the Interactive, Constructive, Active, and Passive (ICAP) framework [9] to understand how LCDLMs could impact student interactive, constructive, active, and passive learning differently from various LCDLM types.

1.1 Low-Cost Desktop Learning Modules (LCDLMs) and Innovative Instructions

Low-Cost Desktop Learning Modules (LCDLMs) are innovative, affordable educational tools designed to enhance hands-on learning experiences in engineering education. These modules serve as small-scale, interactive models of industrial equipment, allowing students to engage directly in complex engineering concepts such as fluid mechanics and heat transfer. Thus far, there are four LCDLMs: Double pipe, Shell and Tube, Hydraulic Loss, and Venturi that are used extensively. Each module was designed to facilitate one specific topic of fluid mechanics and heat transfer. These modules are specifically developed to bridge the gap between theoretical knowledge and practical application, particularly in subjects like fluid mechanics and heat transfer. For instance, in a new module reported by Reynolds et al. development and implementation focused on an evaporative cooling LCDLM, which uses simple, inexpensive materials like expanded aluminum packing media and battery-powered components to demonstrate heat and mass transfer principles [6]. The highly visual and interactive nature of LCDLMs helps to make abstract engineering principles more tangible and understandable, thus facilitating deeper understanding and retention of material learned [8].

Hunsu et al. emphasized that these modules can significantly improve student interest and cognitive engagement by providing a hands-on approach to learning that contrasts with traditional lecture-based methods [10]. LCDLMs are designed to be flexible and adaptable, allowing for various experiments and explorations of engineering phenomena. For example, Van Wie et al. highlighted the versatility of LCDLMs in teaching fluid mechanics and heat transfer through modules like the Venturi meter and double pipe heat exchanger [11]. These studies collectively demonstrated that LCDLMs not only enhance conceptual understanding but also foster a more interactive and engaging learning environment, which is crucial for student success in engineering education [10, 11].

The effectiveness of LCDLMs is well-supported

by their alignment with educational frameworks such as Bloom's Taxonomy and the ICAP hypothesis. Studies, including those by Kaiphanliam et al. [12], have demonstrated that LCDLMs significantly improve student performance at higher cognitive levels, such as analysis and evaluation, compared to traditional lecture methods. This enhancement is particularly crucial in engineering education, where the ability to apply, analyze, and evaluate complex systems is essential. The interactive nature of LCDLMs promotes an active and interactive learning environment, encouraging students to engage more deeply with the material and to develop critical thinking and problem-solving skills that are vital for their future careers.

Furthermore, LCDLMs have been shown to increase student engagement and motivation by offering interactive and constructive learning experiences that go beyond passive information reception [13]. This approach not only enhances learning outcomes but also makes engineering education more inclusive by providing cost-effective alternatives to expensive laboratory equipment. By democratizing access to high-quality educational resources, LCDLMs ensure that a broader range of students can benefit from hands-on learning experiences, thereby supporting a more equitable and effective educational environment. The potential of LCDLMs to transform engineering education highlights the importance of continued research and investment in innovative instructional methods.

Previous research on Low-Cost Desktop Learning Modules (LCDLMs) has shown mixed results regarding their effectiveness in enhancing student learning in engineering education. Some studies have highlighted the significant benefits of using LCDLMs to improve conceptual understanding and engagement. For instance, Van Wie et al. found that hands-on experiences provided by LCDLMs could make abstract engineering concepts more tangible and comprehensible, thus fostering deeper cognitive engagement and retention [11]. These studies indicate that LCDLMs are particularly effective in bridging the gap between theoretical knowledge and practical application, thereby enhancing overall learning outcomes.

However, not all studies have found uniform success across different types of LCDLMs. Research has revealed variability in the effectiveness of specific modules. For example, Kaiphanliam et al. reported that the hydraulic loss module significantly improved student learning outcomes compared to other modules like the Venturi meter and double-pipe heat exchanger [12]. For the hydraulic loss module, the relative simplicity and direct application to fundamental fluid mechanics

concepts were suggested as reasons for its superior effectiveness. In contrast, the Venturi meter and double-pipe heat exchanger, which require a more nuanced understanding of interconnected concepts, showed less dramatic improvements in student performance. This variability underscores the importance of aligning the complexity of the module with the student prior knowledge and the specific learning objectives.

Further complicating the landscape, other studies have shown no significant differences in learning outcomes between different types of LCDLMs, suggesting that factors such as instructor effectiveness, classroom context, and student demographics might also play crucial roles. For instance, Watson et al. indicated that students with lower prior knowledge of engineering concepts tend to benefit more from the use of LCDLMs compared to those with higher prior knowledge [14]. This finding suggests that LCDLMs may be particularly useful in leveling the playing field for students who start with a weaker understanding of the subject matter. Yet, this differential impact raises questions about the best ways to implement these modules to maximize benefits for all students. Collectively, these mixed findings highlight the need for continued research to identify the conditions under which specific LCDLMs are most effective, helping educators better tailor their instructional strategies to meet diverse student needs and optimize learning outcomes.

1.2 The Interactive, Constructive, Active, and Passive (ICAP) Framework

According to the ICAP framework, cognitive engagement activities can be categorized into four modes: interactive, constructive, active, and passive, based on learners' overt learning behaviors [9, 15]. Chi and Wylie stated that with more engagement (i.e., from passive to interactive) with the learning material, learners' learning outcomes increase [9]. Previous research provided evidence that in a more active and interactive engagement learning environment, student learning outcomes were better than passive engagement learning context [16, 17].

The interactive cognitive learning approach fosters students to work collaboratively, exchanging feedback and revising upon feedback, which helps them improve their academic learning and develop interpersonal relationships [9]. Constructive learning behavior is when learners "generate or produce additional externalized outputs or products beyond what was provided in the learning materials" [9, p. 222]. Active learning fosters students to be actively engaged and involved in their learning process. It fosters student interaction with the topic as

opposed to merely receiving information like a traditional lecture with no engagement. Lastly, passive learning does not facilitate the cognitive process for students to be actively engaged in their learning process and might include students passively listening to lectures or receiving the information [9].

Previously, research on ICAP learning theory has demonstrated that participation in hands-on activities or cognitive engagement during learning improves learning [4, 18]. Active learning and a hands-on approach are effective learning approaches, and a meta-analysis of 225 active learning approaches demonstrated that active learning improves student learning compared to traditional learning [4]. Learning through hands-on activities facilitates peer interaction and collaborative learning, which facilitates student deeper engagement. These activities help students learn by actively being involved. Therefore, students find these activities more engaging than passive activities when they learn by doing [19].

LCDLMs enhance learners' deeper level of engagement. LCDLMs require learners to actively operate the modules to investigate fluid mechanics and heat transfer. This process is aligned with the definition of active mode of engagement because it needs "some form of overt motoric action or physical manipulation is undertaken" [9, p. 221]. Furthermore, LCDLM needs the focused attention of students when they are manipulating the modules which is the difference between active and passive activity [9].

Constructive behaviors need students to generate additional "products" beyond what learning materials provide. In LCDLM activities, students use what they learned from the lecture to manipulate the module. To be specific, students have to construct their knowledge and utilize it in completing the LCDLM activities. By doing so, the abstract concepts from the lecture have been constructed by the students to solve the LCDLM problems with self-explanation. Moreover, in the LCDLM activities, students will need to ask questions [5] or pose problems [20], these activities are also categorized as constructive, according to Chi and Wylie [9].

Lastly, LCDLM activities are intended for implementation in chemistry classes as collaborative group exercises. Therefore, students have the opportunity to collaborate with their classmates to complete the activities. For example, students are encouraged to discuss with their peers, ask and answer questions, and clarify their understanding of the concept with their peers. According to the ICAP framework, the discussion between students and the instructor can also be seen as interactive [9].

2. Purpose of Study

LCDLMs have different modules to address various concept topics about fluid mechanics and heat transfer [11]. Therefore, the present study sought to investigate whether different types of LCDLM could influence student engagement and knowledge growth differently. We use ICAP scores to understand different student levels of engagement when manipulating LCDLMs.

The present study focuses on the following research questions:

RQ1: How do various types of LCDLMs influence the ICAP scores?

RQ2: How do various types of LCDLMs influence growth in student knowledge scores?

3. Methods

3.1 Participants

Participants were 2272 undergraduate and graduate students who enrolled in engineering heat transfer and fluid mechanics courses using the LCDLMs from 29 universities in the United States. Data used in this study was collected from Fall 2019 to Spring 2024. Universities, including both public and private institutions, that participated in this study were selected based on their geographical locations. These universities were organized into seven national “hubs” to streamline data collection and management. Students were recruited for the study in their classrooms by their instructors. Before implementation, instructors and their teaching assistants received training. Participation in the present study was voluntary.

Table 1 presents the descriptive analysis results of the participants in this study. A total of 82 participants were removed because they did not complete the ICAP questionnaire. The demographics of the participants showed that most participants were under 22 years old (90.6%). Among all the participants, the majority were Juniors (37.7%), followed by Seniors (11.9%) and Sophomores (6.8%), whereas 42.3% of the participants did not indicate their years in college. Additionally, 56 students reported that they are international students.

3.2 LCDLMs

The Low-Cost Desktop Learning Modules (LCDLMs) allow engineering students to conduct investigations to understand the fundamental principles of fluid mechanics and heat transfer. LCDLMs are modules that simulate standard industry equipment to facilitate a deeper understanding of engineering students of related concepts. These modules provide engineering students with affordable,

simple, and small models of industrial equipment to interact with and understand abstract concepts by observing how these modules work. In the present study, four LCDLMs are employed: Double Pipe, Hydraulic Loss, Shell & Tube, and Venturi (See Figs. 1–4). The Hydraulic Loss and Venturi modules are designed to teach fluid mechanics, whereas the Double Pipe and Shell & Tube modules are designed to teach heat transfer concepts.

3.3 Measurements

3.3.1 Learning Performance

Engineering heat transfer and fluid mechanics cover various topics, such as double pipe and hydraulic loss. This study chose four LCDLM learning topics (i.e., Double Pipe, Hydraulic Loss, Shell & Tube, and Venturi). The research team developed knowledge tests corresponding to each specific topic to measure engineering student knowledge. The knowledge test contains different numbers of questions, ranging from six to nine items. Pre-tests were administered to participants before they were involved in the LCDLM learning activities. The identical post-tests were answered by participants right after they completed the assigned activities (See Appendix for the knowledge instrument). The question formats for both pre-and post-tests include multiple-choice questions, true or false questions, and open-ended questions. Each participant’s performance in the pre-and post-test was graded and calculated by the research team in percentage for further data analyses.

3.3.2 ICAP Questionnaire

The 16-item engagement questionnaire follows the ICAP framework, including interactive, constructive, active, and passive [9]. Each category contains four items, using a 5-point Likert scale (1 = “Strongly Disagree” to 5 = “Strongly Agree”). This questionnaire examines participants’ cognitive engagement in learning with the LCDLMs. The internal consistency of each category indicated that interactive, constructive, and active has good reliability (Cronbach’s $\alpha = 0.89$, 0.89 , and 0.84 , respectively) and passive has excellent reliability (Cronbach’s $\alpha = 0.91$).

3.3.3 Demographics

To better understand the sample’s demographics, this study also collected participants’ gender, age, class year, ethnicity, reason for taking the class, and whether they are international students. All demographic questions were kept anonymous.

3.4 Procedures

This study received approval from the Institutional Review Board. The research team recruited instruc-

tors who taught courses in fluid mechanics, heat transfer, and/or related topics in engineering from the universities in the seven hubs. The LCDLMs were provided to the instructors to include in their classes that fit the topics. Before implementation, instructors and their teaching assistants received comprehensive training from the research design team. These training sessions covered the best practices for integrating LCDLMs into their courses, focusing on fostering student engagement and improving learning outcomes. Participants were first asked to complete the pre-tests to assess their prior knowledge of the to-be-learned topics. During the classes that included LCDLMs, participants were provided with a worksheet to guide their performance of the modules. After the class, participants then answered the post-test, engagement questionnaire, and demographic questionnaire.

3.5 Data Analysis

To examine whether the selected four LCDLMs could influence engineering student engagement differently, a one-way Multivariate Analysis of Variance (MANOVA) was conducted with the topics of LCDLMs as the independent variable and participants' self-reported cognitive engagement as the dependent variables. Each participant's average ICAP scores in the four categories were used in the present study. To understand the effects of LCDLMs on learning outcomes, a one-way Analysis of Variance (ANOVA) was performed to examine the difference in knowledge growth (post-test minus pre-test) among four LCDLMs.

4. Results

4.1 Descriptive Statistics

As shown in Table 1, descriptive statistics were analyzed by using SPSS 28.0. Furthermore, by examining participants' prior knowledge of each topic, we found there was a significant difference ($p < 0.01$). That is, participants, on average, held different levels of prior knowledge before taking the LCDLM activities (e.g., prior knowledge of double pipe was significantly higher than hydraulic loss). To examine the normal univariate distribution, we

examined the skewness and kurtosis values, where skewness varied from -1.03 to 0.71 , and kurtosis ranged from 0.05 to 2.31 for the knowledge growth, interactive, constructive, active, and passive engagement. These indicated that all variables in the present study had the normal univariate distribution [21, 22].

4.2 Engagement

A one-way MANOVA was conducted to answer the first research question. The results showed that there was a statistically significant total MANOVA effect ($F(12, 5775.97) = 2.01, p < 0.05, Wilk's \lambda = 0.99, partial \eta^2 = 0.04$). Specifically, there was a significant effect of LCDLM type on Active score ($F(3, 2186) = 4.42, p < 0.01, partial \eta^2 = 0.06$). The Post Hoc tests indicated that the Active score in the Shell & Tube module ($M = 14.75, SD = 2.97$) was significantly higher than the Hydraulic Loss module ($M = 14.07, SD = 3.08$) and the Venturi module ($M = 14.14, SD = 3.08$). However, there was no statistically significant effect of LCDLM types on interactive, constructive, and passive scores ($ps > 0.05$), please see Table 2.

4.3 Learning Performance

To address the second research question, a one-way ANOVA was performed using knowledge score growth as the dependent variable and LCDLM type as the independent variable. The results showed that there was a significant effect of LCDLM type on knowledge score growth ($F(3, 2200) = 75.53, p < 0.001$). Post Hoc comparisons using the Tukey HSD test found that the mean knowledge growth in the Hydraulic Loss module ($M = 28.17\%, SD = 37.96\%$) is significantly higher than the mean knowledge growth in the Double Pipe module ($M = 8.37\%, SD = 24.66\%$), the Shell & Tube module ($M = 4.75\%, SD = 20.78\%$), and the Venturi module ($M = 9.40\%, SD = 21.23\%$). There was no significant difference among the Double Pipe, Shell & Tube, and Venturi modules; please see Table 3.

5. Discussion

The results of this study provide important insights

Table 1. Means and Standard Deviations of Outcomes for Each Module

	Double Pipe		Hydraulic Loss		Shell & Tube		Venturi	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Interactive	15.78	3.01	15.50	3.10	15.79	3.00	15.54	3.06
Constructive	15.54	3.08	15.18	3.22	15.49	3.01	15.22	3.14
Active	14.45	3.14	14.07	3.08	14.75	2.97	14.14	3.08
Passive	10.07	4.05	9.81	3.81	9.51	3.98	9.76	3.85
Knowledge Growth	8.37%	24.66%	28.17%	37.96%	4.75%	20.78%	9.40%	21.23%

Note: SD = Standard Deviation.

Table 2. MANOVA Results for ICAP Scores as Dependent Variables

Multivariate Tests						
	<i>Wilks' Lambda</i>	<i>F</i>	<i>df1</i>	<i>df2</i>	<i>p</i>	<i>Partial Eta Squared</i>
LCDLMs	0.99	2.01	12	5775.97	<0.05	0.004
Univariate Tests						
	Dependent Variable	Sum of Squares	<i>df</i>	Mean Square	<i>F</i>	<i>p</i>
LCDLMs	Interactive	37.39	3	12.46	1.33	0.262
	Constructive	58.56	3	19.52	2.00	0.112
	Active	126.11	3	42.04	4.42	<0.01
	Passive	74.91	3	24.97	1.62	0.182
Residuals	Interactive	20436.79	2186	9.35		
	Constructive	21333.69	2186	9.76		
	Active	20779.39	2186	9.51		
	Passive	33603.93	2186	15.37		

Table 3. ANOVA Results for Knowledge Growth Scores as Dependent Variables

	<i>Sum of Squares</i>	<i>df</i>	<i>Mean Square</i>	<i>F</i>	<i>p</i>
LCDLMs	205819.74	3	68606.58	75.53	<0.001
Residuals	1998380.31	2200	908.36		

into the effects of different LCDLMs on student engagement and knowledge growth in engineering education, specifically through the lens of the ICAP framework. In line with past literature [13], this study revealed a statistically significant effect of different LCDLM types on the four ICAP engagement categories. The most notable finding was that the Shell & Tube module significantly outperformed the Hydraulic Loss and Venturi modules on the Active score. This suggests that the Shell & Tube module is particularly effective in promoting active engagement, possibly due to its design which may better facilitate hands-on interaction and practical application [11]. These findings imply that while certain LCDLMs can enhance specific types of engagement, the overall impact on all dimensions of engagement may be influenced by other factors. For example, the average pre-test score on the topic of Hydraulic Loss was significantly lower than the other three topics. Therefore, students could find it more difficult to manipulate the Hydraulic Loss LCDLM. To be specific, students in the Hydraulic Loss LCDLM activity could be more “passive” to participate. However, our results also found that LCDLM did promote student interactive and constructive engagement behaviors ($M = 15.64$ and $M = 15.35$, respectively). And for all four LCDLMs, student passive engagement behavior was low ($M = 9.83$). Therefore, LCDLMs can be implemented to enhance engineering students higher level of cognitive engagement while instructors should be aware of various factors, such as students prior knowledge, that could influence the effectiveness of LCDLMs.

This study extends previous research to examine the effect of LCDLMs on knowledge growth. The result revealed that the Hydraulic Loss module led to significantly higher knowledge growth compared to the Double Pipe, Shell & Tube, and Venturi modules. This finding underscores the Hydraulic Loss module’s effectiveness in enhancing student understanding and knowledge growth. Interestingly, there were no significant differences in knowledge growth among the Double Pipe, Shell & Tube, and Venturi modules, indicating that these modules may have similar impacts on learning outcomes despite their structural differences [11]. One possible explanation for this difference could be the lower prior knowledge levels of students before participating in the Hydraulic Loss LCDLM activity. This could imply that LCDLMs could be an ideal instructional tool, especially for students with relatively little prior knowledge or with misconceptions about the to-be-learned topic [11, 14]. As mentioned above, LCDLMs help to make engineering principles more tangible and understandable. Students could find it difficult to follow the lectures which caused their lower levels of prior knowledge, however, LCDLMs help to clarify their confusion and facilitate deeper cognitive engagement.

The results highlight the importance of selecting appropriate LCDLM types to maximize student engagement and knowledge growth. The significant impact of the Shell & Tube module on active engagement and the Hydraulic Loss module on knowledge growth suggests that different LCDLMs may be best suited for different educational objectives. Educators should consider these

findings when designing curriculum and instructional strategies to ensure that the chosen tools align with their specific teaching goals.

6. Limitations and Future Directions

This study does have limitations. First, due to the implementation of a large sample size, we cannot match the ICAP score with students knowledge growth perfectly. This is because some instructors or their teaching assistants did not successfully implement both the ICAP questionnaire and the pre- and post-assessments for each implementation. Consequently, we sometimes received only ICAP data or only pre- and post-knowledge data, but not both. However, future research is warranted to examine how students engagement interacts with their knowledge. Especially, the question of what is the role of prior knowledge in the LCDLMs needs further investigation. Second, the present study did not fully consider the instructor's roles in the LCDLM activities. For example, the interaction between instructor and students in manipulating LCDLM could significantly influence students learning and engagement. Future research could take instructors' roles in the LCDLM activities into consideration to understand how instructors could better facilitate LCDLM activities.

Future research should also investigate the underlying factors that contribute to the effectiveness of different LCDLMs further. Studies could explore how specific design features influence engagement and learning outcomes, and whether combining elements from multiple modules could enhance overall effectiveness. Additionally, longitudinal studies are needed to assess the sustained

impact of these instructional tools on student performance and engagement over time. Integrating student feedback and adapting LCDLMs based on empirical findings will be crucial for refining these educational resources and maximizing their benefits in engineering education. Overall, this study contributes to the growing body of literature on the use of LCDLMs in engineering education, providing valuable insights into their impact on student engagement and learning outcomes through the ICAP framework.

7. Conclusion

This study highlighted the effectiveness of Low-Cost Desktop Learning Modules (LCDLMs) in enhancing student engagement and knowledge in engineering education, underscoring their usefulness in improving student engagement and knowledge growth through active, constructive, and interactive learning processes. By leveraging the ICAP framework, we demonstrated that various types of LCDLMs influence student engagement and learning outcomes in distinct ways. Notably, the Shell & Tube module excelled in promoting active engagement, while the Hydraulic Loss module significantly boosted knowledge growth. The findings emphasize that selecting the appropriate LCDLM type is crucial, as different modules, like the Shell & Tube for engagement and Hydraulic Loss for knowledge growth, serve distinct educational benefits.

Acknowledgments – This research was supported by a grant from the National Science Foundation through the Division of Undergraduate Education under award numbers 1432674 & 1821578 and IUSE supplement DUE-1545654

References

1. F. Meng, B. J. Van Wie, D. B. Thiessen and R. F. Richards, Design and fabrication of very-low-cost engineering experiments via 3-D printing and vacuum forming, *International Journal of Mechanical Engineering Education*, **47**(3), pp. 246–274, 2018.
2. T. Seechaliao, Instructional strategies to support creativity and innovation in education, *Journal of Education and Learning*, **6**(4), pp. 201–208, 2017.
3. R. Wylie and M. T. H. Chi, The self-explanation principle in multimedia learning, in R. E. Mayer (Ed.), *The Cambridge Handbook of Multimedia Learning*, Cambridge University Press, 2nd edn, pp. 413–432, 2014.
4. S. Freeman, S. L. Eddy, M. McDonough, M. K. Smith, N. Okoroafor, H. Jordt and M. P. Wenderoth, Active learning increases student performance in science, engineering, and mathematics, *Proceedings of the National Academy of Sciences—PNAS*, **111**(23), pp. 8410–8415, 2014.
5. A. C. Graesser and N. K. Person, Question asking during tutoring, *American Educational Research Journal*, **31**(1), pp. 104–137, 1994.
6. O. M. Reynolds, A. I. Khan, D. B. Thiessen, P. Dutta, O. O. Adesope and B. J. Van Wie, Development and Implementation of a Low-Cost Desktop Learning Module for Double Pipe Heat Exchange, *Chemical Engineering Education*, **56**(2), pp. 103–112, 2022.
7. A. I. Khan, N. B. Pour, K. Bryant, D. B. Thiessen, O. O. Adesope, B. J. Van Wie and P. Dutta, Effectiveness of hands-on desktop learning modules to improve student learning in fluid mechanics and heat transfer across institutions and program types, *International Journal of Engineering Education*, **38**(3), pp. 849–872, 2022.
8. O. M. Reynolds, B. J. Van Wie, H. Curtis, J. Gartner, K. Dahlke, O. O. Adesope and P. Dutta., Teaching fluid mechanics and heat transfer in hands-on and virtual settings with low cost desktop learning modules, *International Journal of Engineering Education*, **38**(5) pp. 1–14, 2022.
9. M. T. H. Chi and R. Wylie, The ICAP framework: Linking cognitive engagement to active learning outcomes, *Educational Psychologist*, **49**(4), pp. 219–243, 2014.
10. N. J. Hunsu, O. Adesope and B. J. Van Wie, Engendering situational interest through innovative instruction in an engineering classroom: what really mattered?, *Instructional Science*, **45**(6), pp. 789–804, 2017.

11. B. J. Van Wie, Z. Durak, O. M. Reynolds, K. Kaiphanliam, D. Thiessen, O. O. Adesope O. J. Ajeigbe, A. I. Khan, P. Dutta, H. Curtis, C. Watson and J. Gartner, *Development, dissemination and assessment of inexpensive miniature equipment for interactive learning of fluid mechanics, heat transfer and biomedical concepts*, in ASEE 2022 Annual Meeting: Excellence Through Diversity, Minneapolis, MN, United States, 2022.
12. K. M. Kaiphanliam, A. Nazempour, P. B. Golter, B. J. Van Wie and O. O. Adesope, Efficiently assessing hands-on learning in fluid mechanics at varied Bloom's taxonomy levels, *International Journal of Engineering Education*, **37**(3), pp. 624–639, 2021.
13. O. J. Ajeigbe, T. A. Oni, O. J. Sunday, O. O. Adesope, O. Oje, B. J. Van Wie, J. Gartner, P. Dutta and D. B. Thiessen, *Enhance engineering education: A comparative analysis of Low-Cost Desktop Learning Module impact student engagement and outcomes*, in 2024 The Future of Engineering Education Annual Conference & Exposition, Portland, OR, United States, 2024.
14. C. E. Watson, J. Gartner, B. J. Van Wie, P. Dutta, O. O. Adesope and H. Curtis, *The effect of prior knowledge on learning with Low-Cost Desktop Learning Modules*, in ASEE 2022 Annual Meeting: Excellence Through Diversity, Minneapolis, MN, United States, 2022.
15. M. T. H. Chi, Active-Constructive-Interactive: A conceptual framework for differentiating learning activities, *Topics in Cognitive Science*, **1**(1), pp. 73–105, 2009.
16. M. Hernández-de-Menéndez, A. Vallejo Guevara, J. C. Tudón Martínez, D. Hernández Alcántara and R. Morales-Menendez, R. Active learning in engineering education. A review of fundamentals, best practices and experiences, *International Journal on Interactive Design and Manufacturing (IJIDeM)*, **13**(3), pp. 909–922, 2019.
17. A. Mirkouei, R. Bhinge, C. McCoy, K. R. Haapala and D. A. Dornfeld, A pedagogical module framework to improve scaffolded active learning in manufacturing engineering education, *Procedia Manufacturing*, **5**, pp. 1128–1142, 2016.
18. K. L. Smart and N. Csapo, Learning by doing: Engaging students through learner-centered activities, *Business Communication Quarterly*, **70**(4), pp. 451–457, 2007.
19. D. L. Haury and P. Rillero, *Perspectives of hands-on science teaching*, ERIC Clearinghouse for Science, Mathematics and Environmental Education, Columbus, Ohio, 1994.
20. J. P. Mestre, Probing adults' conceptual understanding and transfer of learning via problem posing, *Journal of Applied Developmental Psychology*, **23**(1), pp. 9–50, 2002.
21. B. M. Byrne, *Structural equation modeling with AMOS: Basic concepts, applications, and programming*. New York: Routledge, 2010.
22. J. F. Hair, W. C. Black, B. J. Babin and R. E. Anderson, *Multivariate data analysis* (7th ed.), Pearson Educational International, 2010.

Appendices

Appendix A. Low-Cost Desktop Learning Modules (LCDLMs)

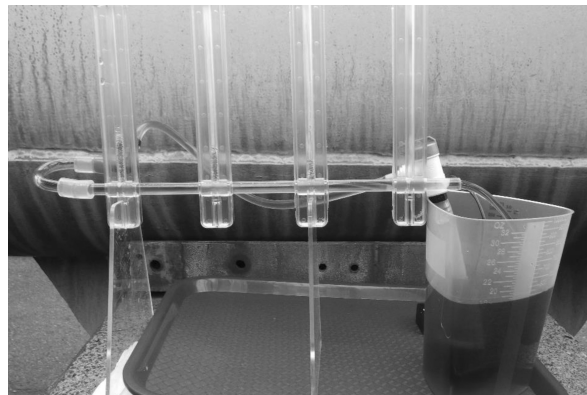


Fig. 1. Hydraulic-loss setup.



Fig. 2. Venturi setup

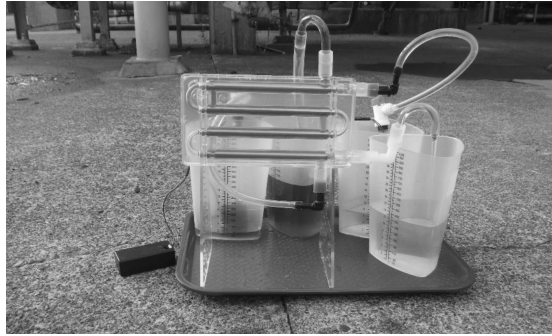


Fig. 3. Double-pipe heat exchanger setup.

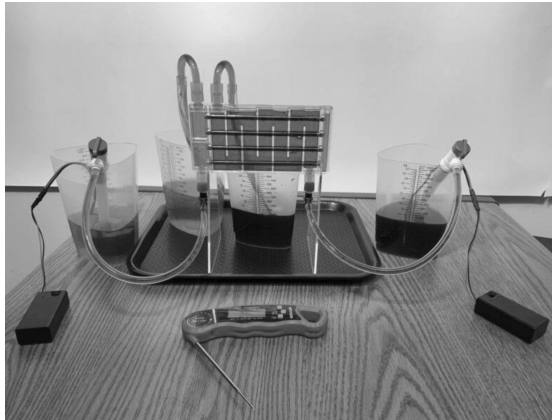


Fig. 4. Shell-and-tube heat exchanger setup.

Appendix B. Knowledge Tests

Hydraulic Loss Knowledge Test

Head losses

Excessive pressure (head) losses are observed in a section of piping with constant diameter. Select the option that could be explored to reduce the head losses in the piping section, assuming turbulent flow.

- Increase the fluid velocity.
- Decrease the pipe diameter.
- Increase the pipe diameter.
- Use a piping material with a higher relative roughness to decrease the friction factor.

Velocity in a coil

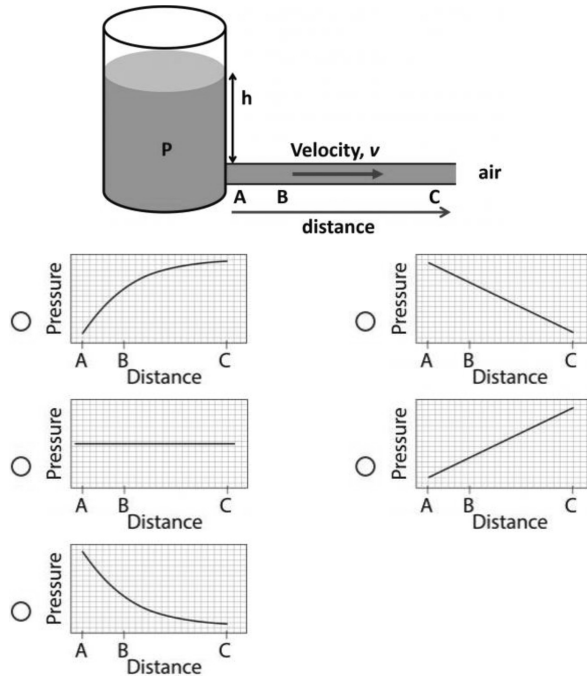
Imagine fluid flowing inside the coil shown below. Assuming the coil has a constant diameter, what would happen to the fluid velocity as the fluid flows from the top to the bottom of the coil?



- The velocity will increase because the fluid is flowing downwards and is driven by gravity.
- The velocity will remain constant because the pipe has a constant diameter and mass must be conserved.
- The velocity will decrease because of friction on the pipe walls.
- The velocity will remain constant because the increase in velocity due to gravitational forces is counterbalanced by the decrease due to friction.

Pressure v. distance

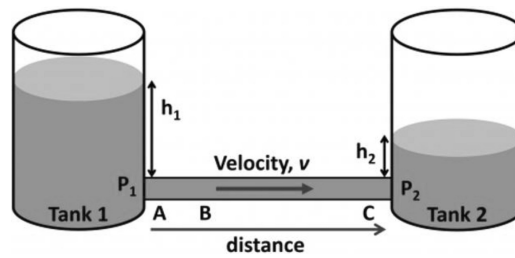
Below is a steady state system where fluid is flowing from a tank with a constant liquid height, h , at some pressure, P , through a pipe to the atmosphere. What is the relationship between **pressure** and **distance** in the pipe?



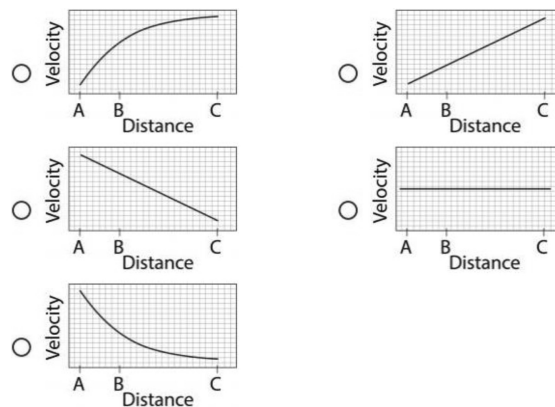
Because . . .

- Frictional losses within the pipe will decrease velocity nonlinearly, so pressure must also decrease nonlinearly.
- Frictional losses within the pipe will decrease pressure linearly.
- The fluid is not accelerating, so the pressure must be constant.
- Frictional losses within the pipe will increase pressure.
- The fluid speeds up through the pipe, so pressure must decrease.

Velocity v. distance



Water flows through a pipe from Tank 1 to Tank 2. The water level in each tank is indicated at an instance in time. Assuming steady-state flow, select the correct graph of **velocity** versus **distance** down the pipe.



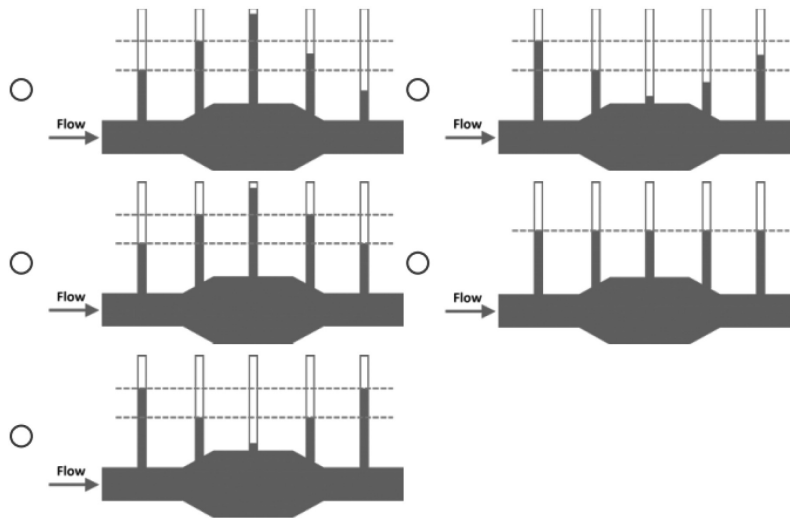
Because . . .

- The force of friction reduces the velocity of the liquid.
- The velocity increases near the pipe entrance because of the pressure gradient, but accelerates slowly at the pipe exit because of friction.
- The cross sectional area is constant, thus the velocity is constant to conserve mass.
- The velocity increases down the pipe because of the pressure gradient.
- The velocity decreases near the pipe entrance due to friction and then decelerates since friction is reduced when it moves slower.

Venturi Knowledge Test

Expansion with standpipes

Select the figure that most closely represents reality, assuming incompressible flow and that the diameters at points A and C are equal.



Energy transition

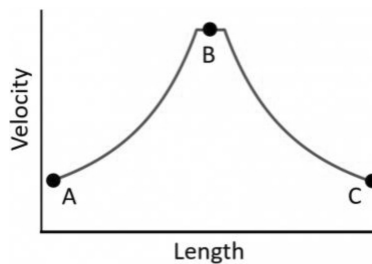
Describe the energy transformation in the fluid between points A and B.



- Kinetic energy is being converted to flow work.
- Flow work is being converted to kinetic energy.
- Kinetic energy is being converted to potential energy.
- Potential energy is being converted to kinetic energy.
- Not enough information.

Pressure from velocity profile

In a horizontal pipe of changing diameter, the following velocity profile was measured at points A, B, and C. Choose the best description for the pressure profile, assuming $v_A = v_C$.

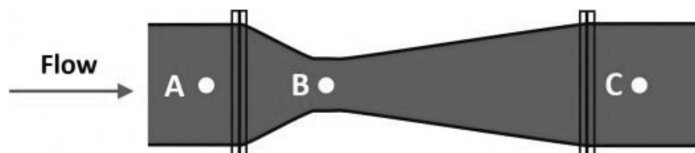


- $P_A > P_B > P_C$ because friction causes the pressure to decrease along the entire length of the pipe.

- $P_A > P_C > P_B$ because the velocity increases at Point B, leading to a decrease in pressure, and $P_C < P_A$ because of frictional losses, though the velocity is the same.
- $P_B > P_A > P_C$ because the velocity increases at Point B, leading to an increase in pressure, and $P_C < P_A$ because of frictional losses, though the velocity is the same.
- $P_A = P_C > P_B$ because the velocity increases at Point B, leading to a decrease in pressure, and the pressures at $P_A = P_C$ because the velocities are the same.

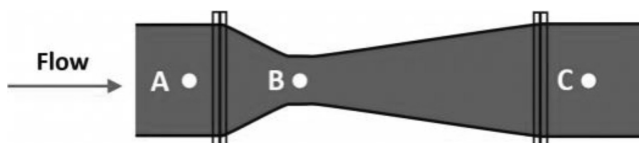
Pressure and velocity v. distance

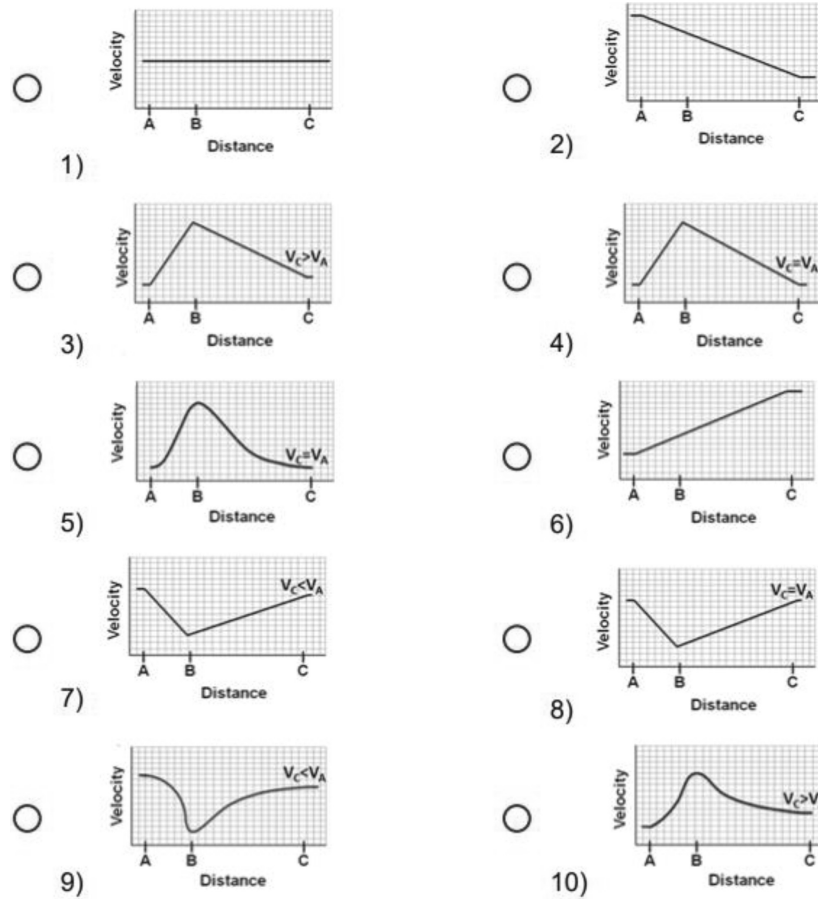
Consider the Venturi meter below. Select the most realistic graph for pressure versus distance in the venturi:



- | | | | |
|-----------------------------|--|-----------------------------|--|
| <input type="radio"/>
1) | | <input type="radio"/>
2) | |
| <input type="radio"/>
3) | | <input type="radio"/>
4) | |
| <input type="radio"/>
5) | | <input type="radio"/>
6) | |
| <input type="radio"/>
7) | | <input type="radio"/>
8) | |
| <input type="radio"/>
9) | | | |

Select the most realistic graph for velocity versus distance in the Venturi:





Continuity T/F

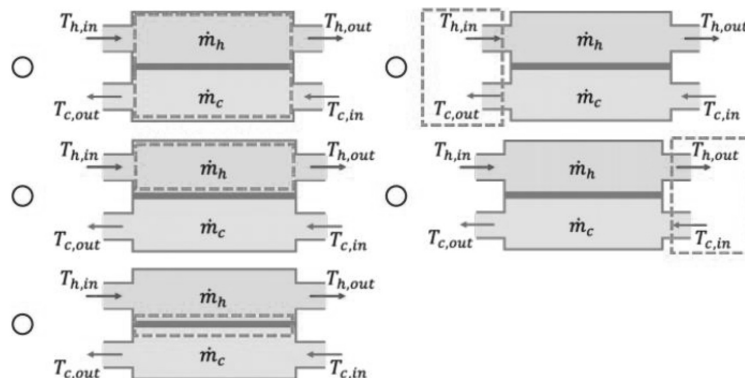
To describe the concept of continuity at **steady state** for an **incompressible fluid**, classify the following statements as true or false:

	True	False
Mass flow rate in equals mass flow rate out	<input type="radio"/>	<input type="radio"/>
Volumetric flow rate in equals volumetric flow rate out	<input type="radio"/>	<input type="radio"/>
As diameter increases, velocity increases	<input type="radio"/>	<input type="radio"/>

Double Pipe Knowledge Test

System boundary

Below is a simple heat exchanger schematic with different system boundaries indicated by green dashed boxes. **Using an energy balance to determine the rate of heat transfer, Q, into the cold fluid from the hot fluid, which would you pick as the system to analyze?** Think about which temperatures you would need to solve for $Q = mCp\Delta T$.



Double pipe length

Consider two double-pipe, parallel-flow heat exchangers that are identical except that one is two times longer than the other one. If flow rates and inlet conditions are the same, which of the exchangers is more likely to have a higher heat transfer rate?

- Longer one.
- Shorter one.
- Same in both heat exchangers.

Because . . .

- Heat transfer does not depend on the length of the heat exchangers.
- Having a constant mass flow rate and heat capacity should yield the same heat transfer rate.
- The longer tube length offers a higher surface area for heat transfer.
- The longer tube length provides a larger residence time.
- Shorter tube length offers higher velocity through the tube which offers higher heat transfer rates.

Areas for flow and heat exchange

Cold water flows through the annulus of a see-through heat exchanger shown below. Match the areas in green to their descriptions (the clear outline represents the outer tubing):

Items

Note: cold water is see-through along the pipe in this image

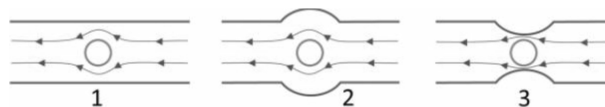
Note: the exchanger is cut across the red cross-section

Area for cold water flow

Area for hot water flow

Tube in a duct

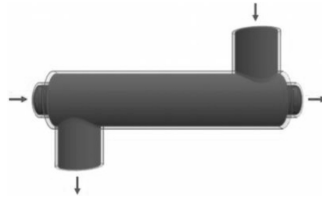
To remove heat at the highest possible rate from a hot tube placed in a duct with cold flow, which setup would you choose, assuming *flow rate is the same* in each case?



- Setup (2) because it will provide the lowest fluid velocity passing over the duct.
- Setup (1) because it offers a balance between velocity and pressure drop passing over the duct.
- Setup (3) because it will offer the highest possible fluid velocity passing over the duct.
- All setups will give the same rate of heat transfer because flow rate is the same in each case.

Process control

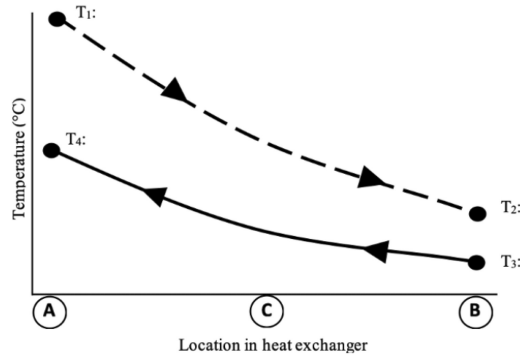
Select all options that would increase the temperature of the hot water outlet (if all other parameters remain the same) in the heat exchanger below:



- Reduce the cold-water flow rate.
- Reduce the hot-water flow rate.
- Add an insulated jacket to the outer cold-water pipe.
- Increase the cold-water temperature.

Temperature driving force

In the diagram, each line represents a temperature profile for one fluid along the length of a countercurrent exchanger. Which temperature differences drive heat transfer? Select all that apply.



- T1—T4.
- T1—T2.
- T1—T3.
- T2—T4.
- T2—T3.
- T4—T3.

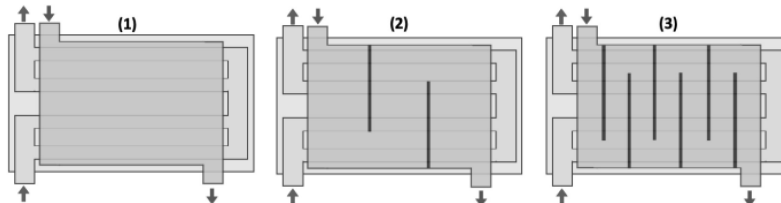
Does the driving potential for heat transfer change throughout the exchanger?

- Yes
- No

Shell & Tube Knowledge Test

S&T Baffle Pitches

To remove heat at the highest possible rate from tubes containing hot water in a shell and tube heat exchanger, which setup would you choose for the cold water on the shell side to maximize heat transfer? Assume the cold fluid flow rate and heat exchanger size are the same across all cases.



- Setup (1) because it will provide the lowest fluid velocity passing over the tube side giving more residence time for heat to transfer.
- Setup (2) because the shell-side velocity is increased due to the smaller cross-sectional area, which increases turbulence (Re) and, therefore, increases the heat transfer coefficient but is balanced with a medium residence time.
- Setup (3) because the shell-side velocity is the highest out of all setups due to the smallest cross-sectional area for flow, which increases turbulence (Re) and, therefore, increases the heat transfer coefficient.
- Setup (3) because the shell-side fluid has a longer pathway and therefore the highest residence time.
- All setups will give the same rate of heat transfer because flow rates and heat exchanger size are the same in each case.

Area for heat exchange

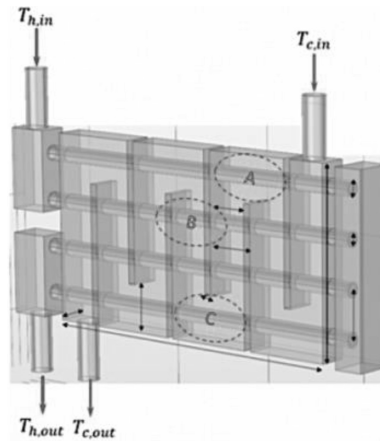
What area would you use for A_i in $\dot{Q} = U_i A_i \Delta T_{LM}$ in a shell and tube heat exchanger?

- D_i = inner diameter of tube
- L = tube length
- D_o = outer diameter of tube
- N_t = total number of tubes

- $\frac{\pi}{4} D_i^2 N_t$
- $\pi(D_o - D_i) L N_t$
- $\pi D_i L$
- $\frac{\pi}{4} (D_o^2 - D_i^2)$
- $\pi D_i L N_t$

Types of flow

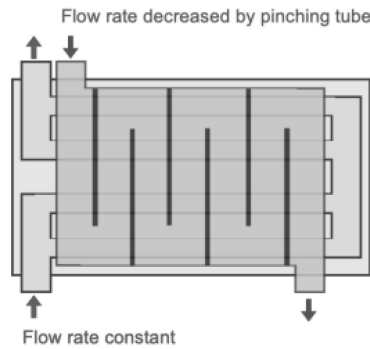
For the following arrangement of a shell & tube heat exchanger what types of flows are occurring in regions A, B, and C (identified by red circles)?



	Counter Flow	Cross Flow	Parallel Flow
A	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
B	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
C	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Process Controls

Cold (blue) and hot (red) water flow through the shell and tube sides, respectively. If you were to reduce the flow rate of the shell (cold) side by pinching the tube, for example, what would happen to the exit temperature of the hot water in comparison to the previous temperature?



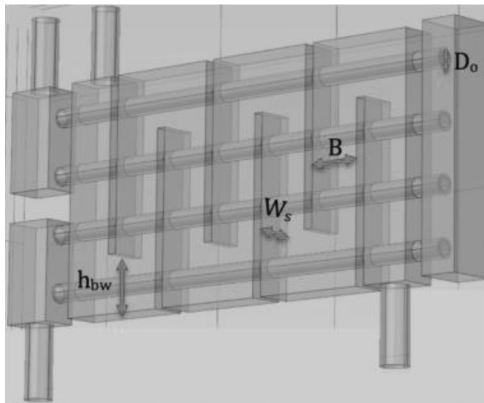
The hot water outlet temperature will . . .

- Increase.
- Decrease.
- Stay the same.

Because . . .

- The reduced flow rate on the shell side decreases the average velocity and, therefore, increases the heat transfer resistance and decreases the heat transfer coefficient on the shell side.
- Pinching causes a jetting effect, which increases the velocity and reduces the residence time of the cold fluid resulting in less time for heat transfer.
- Pinching causes a jetting effect, which increases the velocity and reduces the shell side resistance to heat transfer, making the shell side heat transfer coefficient larger.
- The reduced flow rate will allow the cold fluid to stay in the system longer, increasing the residence time, allowing more time for heat transfer from the hot fluid.
- The flow on the tube-side remains in the turbulent regime, so the heat transfer rate on that side still dominates.

Baffle Window Flow Area

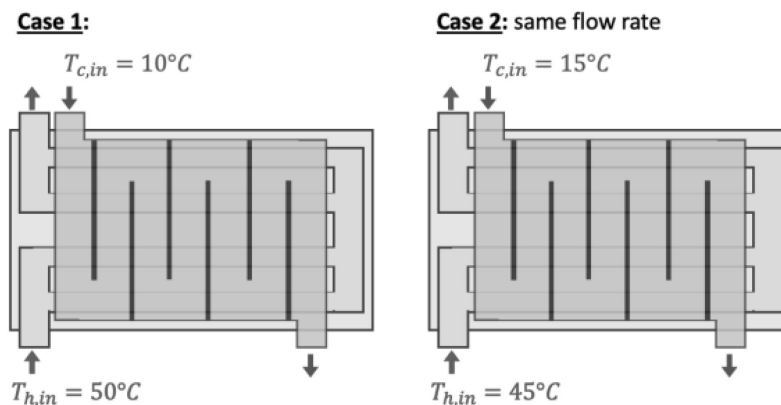


To determine the fluid velocity, \bar{v}_o , on the shell side, we must divide the shell-side volumetric flow rate, \dot{V}_o , by which area, A ?:

- $A = \pi D_o N_{tube}$
- $A = B \cdot (W_s - D_o)$
- $A = h_{bw} \cdot W_s - \frac{\pi D_o^2}{4}$
- $A = \sqrt{(h_{bw} \cdot W_s - \frac{\pi D_o^2}{4}) \times (B \cdot (W_s - D_o))}$

Driving Force

Cold (blue) and hot (red) water flow through the shell and tube sides, respectively. If you were to reduce the temperature difference between the hot and cold inlets by increasing the cold-water inlet temperature and decreasing the hot-water inlet, what will happen to the **heat transfer rate** between Cases 1 and 2? Assume flow rates stay the same between the two cases.



The heat transfer rate in Case 2 will . . .

- Increase.
- Decrease.
- Stay the same.
- Not enough information.

Gan Jin is a PhD candidate in Educational Psychology at Washington State University. His research focuses on multimedia learning, conceptual change, cognition, and motivation in STEM education. He explores how computer-based multimedia and interactive instructional strategies can foster deep learning. Additionally, he emphasizes the role of motivational factors, such as engagement, emotion, and interest, in shaping students' learning experiences. Gan's research investigates the dynamic interplay between learners' motivation and cognition, examining how this interaction influences effective learning outcomes.

Talodabolorun Anne Oni is an Electrical Engineering graduate from the Voiland School of Engineering and Architecture, Washington State University, Pullman.

Florence Adesope is a PhD student in Civil Engineering with a focus on Construction, Energy, and Sustainable Infrastructure at the University of Washington. With a background in civil engineering and project management, her research interests are in sustainability in infrastructure, particularly in vulnerable community spaces. She hopes to explore how infrastructure systems can be designed and managed to aid in a resilient and sustainable future for everyone, especially those in marginalized populations. Florence is committed to advancing sustainability within the field of civil engineering.

Blessing Akinrotimi is a PhD student in Educational Psychology at Washington State University with research interests in the learning sciences, conceptual change, and multimedia learning. She investigates how learners develop misconceptions in STEM fields and identifies instructional strategies that effectively address and correct misconceptions. Blessing's current focus examines the role of learners' emotions when engaging with refutation texts or instructions designed to correct misconceptions. By exploring how positive and negative emotional responses influence motivation, engagement, and learning outcomes, she aims to enhance instructional strategies that promote deeper conceptual understanding and improved learning experiences in STEM disciplines.

Olusola Olalekan Adesope is a Boeing Distinguished Professor of STEM Education at Washington State University-Pullman. Dr. Adesope's research focuses on the use of systematic-reviews/meta-analyses for advancing evidence-based practices, cognitive/pedagogical underpinnings of learning with computer-based multimedia resources, and investigation of instructional principles and assessments in STEM education. He has over 170 published journal papers, book chapters and proceedings and has presented over 125 national and international conference papers. He is an editor for different premier journals including being the co-Editor for *Educational Researcher*, a Senior Associate Editor for the *Journal of Engineering Education*, and Associate Editor of the *Journal of Educational Psychology*.

Oluwafemi J. Ajeigbe is a PhD student in Electrical Engineering at Texas A&M University, with research interests that encompass both cyber-physical system security and engineering education. His work with the NSF-funded EDUC-ATE project, which focuses on enhancing engineering pedagogy through interactive learning modules, has provided him with profound insights into effective student engagement and educational success. Concurrently, Oluwafemi is deeply committed to improving the robustness, resilience, and security of cyber-physical systems. This dual focus allows him to approach the field of engineering with a comprehensive and innovative perspective, seeking solutions that are both technologically advanced and educationally impactful.

Oluwafemi Sunday, PhD is an assistant professor of educational psychology specializing in the intersection of educational psychology, learning sciences, instructional design, and technology. His research delves into the cognitive and pedagogical aspects of learning with computer-based multimedia, focusing on knowledge representation through interactive concept maps and diagrams, evidence-based practices, learning analytics, and instructional principles in STEM education. Dr. Sunday has pioneered the use of eye-tracking technology to analyze learners' cognitive processes and is committed to advancing the field through both scholarship and teaching. His future research plans include the application of psychophysiological indicators such as Galvanic Skin Response (GSR) and eye-tracking technology to dissect learners' cognitive and emotional processes during multimedia learning activities.

Prashanta Dutta is the Richard Schneider Jr. Professor in the School of Mechanical and Materials Engineering at Washington State University. He has received his PhD degree in Mechanical Engineering from Texas A&M University in 2001. He started his academic career at the School of Mechanical and Materials Engineering at 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) and a member of the Washington State Academy of Sciences. He has authored and co-authored more than 200 peer-reviewed journal and conference papers and delivered more than 75 invited talks worldwide. Currently, he serves as a Deputy Editor for the *Electrophoresis*.

Bernard J. Van Wie received his BS, MS, and PhD, and did his postdoctoral work at the University of Oklahoma where he also taught full courses as a graduate student and as a visiting lecturer. He has been on the Washington State University (WSU) faculty for 41 years and for the past 27 years has focused much of his effort on developing, implementing, assessing, and propagating use of hands-on modules and interactive exercises that can be used in standard lecture classrooms, so students do not need to wait till their senior year to see examples of process equipment. He also leads a strong program in bioreactor design for biomanufacturing of cartilage tissue and cells for immunotherapy.