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Teaching Fluid Mechanics and Heat Transfer in Hands-on and Virtual Settings with Low Cost Desktop Learning Modules*

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Although there is extensive literature documenting hands-on learning experiences in engineering classrooms, there is a lack of consensus regarding how student learning during these activities compares to learning during online video demonstrations. Further, little work has been done to directly compare student learning for similarly-designed hands-on learning experiences focused on different engineering subjects. As the use of hands-on activities in engineering continues to grow, understanding how to optimize student learning during these activities is critical. To address this, we collected conceptual assessment data from 763 students at 15 four-year institutions. Students completed activities with one of two highly visual low-cost desktop learning modules (LCDLMs), one focused on fluid mechanics and the other on heat transfer principles, using two different implementation formats: either hands-on or video demonstration. Conceptual assessment results showed that assessment scores significantly increased after all LCDLM activities and that gains were statistically similar for hands-on and video demonstrations, suggesting both implementation formats support an impactful student learning experience. However, a significant difference was observed in effectiveness based on the type of LCDLM used. Score increases of 31.2% and 24% were recorded on our post-activity assessment for hands-on and virtual implementations of the fluid mechanics LCDLM compared to pre-activity assessment scores, respectively, while significantly smaller 8.2% and 9.2% increases were observed for hands-on and virtual implementations of the heat transfer LCDLM. In this paper, we consider existing literature to ascertain the reasons for similar effectiveness of hands-on and video demonstrations and for the differing effectiveness of the fluid mechanics and heat transfer LCDLMs. We discuss the practical implications of our findings with respect to designing hands-on or video demonstration activities.

Keywords: hands-on learning; virtual demonstration; COVID-19

1. Introduction

There is extensive research evidence showing that active learning approaches in STEM courses positively impact student understanding and engagement [1, 2]. One popular type of active learning, hands-on learning, allows students to engage with material and experience real-world phenomena to learn concepts rather than simply modeling problems in a traditional classroom setting. Further, interactive activities, where students work with their peers to construct understanding of conceptual information based on an exchange of ideas, have been shown to be particularly beneficial for improving conceptual understanding compared to other types of active learning [3–5]. Motivated by this, our group developed a number of highly visual, miniature low-cost desktop learning modules (LCDLMs) demonstrating hydraulic loss, flow measurement, and heat transfer in an interactive classroom setting. We successfully implemented these modules in chemical and mechanical engineering courses at our own university and data support that these visual representations of engineering phenomena lead to better understanding of several concepts such as identifying the system boundary used to calculate heat transfer rate in a simple heat exchanger and predicting the velocity

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trend and pressure profile in a pipe [6–8]. Further, our findings show that LCDLMs can be used to trigger and maintain student situational interest due to the novelty of innovative instructional intervention and meaningfulness of the activity for real-life applications in fluid mechanics and heat transfer [9]. Hands-on activities have been shown to be broadly beneficial for student learning compared to traditional lecture; however, several studies indicate they may be less beneficial for improving performance on measures only minimally related to the hands-on activity, such as general exam questions focused on overarching concepts [10, 11]. This suggests a need to further study what students learn during hands-on experiences and how to accurately assess that learning.

The COVID-19 pandemic led to an urgent need to develop strong virtual alternatives to hands-on in-person experiences. Apart from use during the pandemic, virtual materials that replace or supplement hands-on laboratories will be useful for distance education as well as a complement to hands-on experiments. Videos have been shown to be a viable alternative to face-to-face lecture in a recent systematic review of 105 studies by Noetel et al. [12] who found that replacing traditional instruction or reading with video-based instruction in undergraduate courses resulted in a significant overall weighted mean effect on student learning with a small effect size (g = 0.28) while adding videos to existing teaching approaches resulted in a large overall weighted mean effect size (g = 0.80). Video has also been used to effectively replace in-person demonstrations, as shown by Kestin et al. [13] who found that replacing live experimental demonstrations on projectile and rolling object velocity with video demonstrations in a physics course led to 25-30% better performance on a conceptual assessment. Finally, virtual materials have been used to enhance or replace traditional hands-on laboratories in several studies. For example, after using virtual labs as pre-lab material in a bioengineering laboratory, Domingues et al. [14] found that 30% more students were prepared for and could execute hands-on laboratories, and that 25% more students effectively interpreted and discussed results compared to students who only completed in-person labs. Similarly, Craddock found introducing a multimedia pre-lab manual to an environmental engineering course helped 67% of students feel they were more prepared for laboratory procedures and results interpretation than if a printed manual were used [15]. Further, Wiesner and Lan's comparison of virtual and hands-on laboratories in a unit operations course showed students performed equally well on conceptual assessments for two of three laboratories and 75% of students recommended a combination of physical and virtual laboratories [16]. Given the positive reception by students and conceptual effectiveness of many virtual materials, further investigation into their use for a variety of activities is warranted.

In response to the COVID-19 pandemic, we developed a series of virtual demonstration videos to replace hands-on LCDLM implementations for spring 2020 and fall 2021. In this study, we examine conceptual understanding gains for hands-on and virtual demonstration implementations, a comparison which, to our knowledge, has not been well-explored in existing literature. Further, we assess two LCDLMs: a hydraulic loss module focused on fluid mechanics and a double pipe heat exchanger focused on heat transfer principles. We sought to answer two research questions by comparing results collected at 15 institutions in hands-on or virtual implementation settings:

(1) Are there significant differences in understanding gains observed after hands-on or virtual activities and;
(2) Does the module and associated activity used during implementation have a significant effect on understanding gains and if so why are there differences?

By answering these questions, we seek to further understand whether interactive, hands-on experiments can be effectively transitioned to a virtual demonstration format in engineering classrooms and whether the effectiveness of hands-on and virtual tools depends on the content of experiments, supporting materials, and assessments.

2. Methods

2.1 Module Description and Project Objectives

The hydraulic loss and double pipe LCDLM are both highly visual, low-cost, small-scale replicas of industrial equipment constructed using injection molding and robotically assisted adhesive application. Fig. 1A and 1B show the experimental set-up for each module, used directly by students during hands-on classes and demonstrated during virtual implementations. The hydraulic loss module consists of a straight, constant diameter pipe with four standpipe manometers along the length which allows students to observe head loss. The double pipe heat exchanger consists of a transparent annular shell surrounding stainless steel tubes which allows students observe flow patterns of annular- and tube-side fluids. Flow of colored water is achieved with battery operated pumps. Students measure flow rate in both modules, manometer height in the hydraulic loss module for calculation of the pressure drop, and fluid temperatures in the

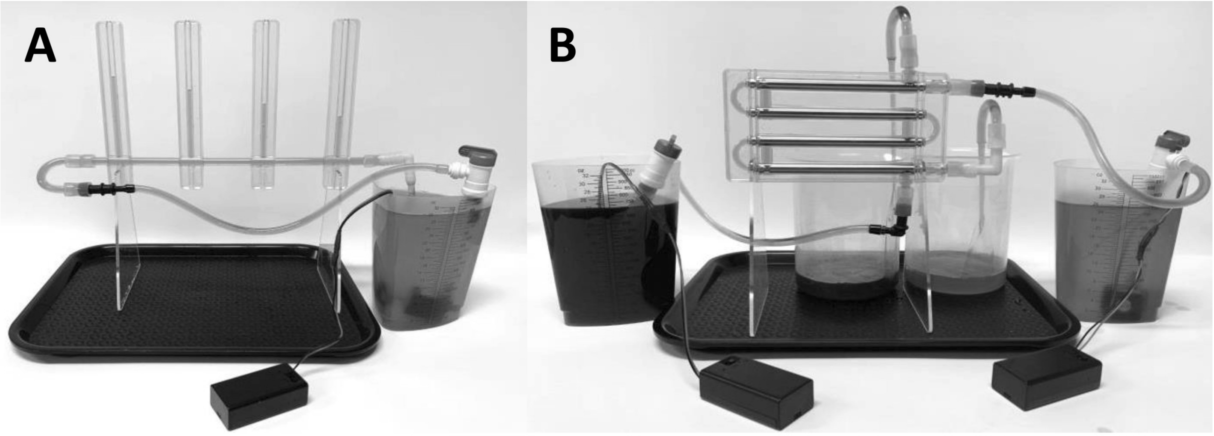

Fig. 1. (A) Hydraulic loss module and (B) double pipe heat exchanger experimental set ups used in hands-on and virtual demonstration implementations.

double pipe heat exchanger for calculation of the heat transfer rate.

Data presented in this manuscript was collected as part of an ongoing effort to disseminate and evaluate LCDLMs at 15 four-year institutions across the United States. We distributed LCDLM kits, which are not currently publicly available for purchase, to each implementing institution and provided implementers with training at regional workshops and standardized worksheet and assessment materials to accompany LCDLM activities. To preserve a sense of institutional autonomy and maximize the adoption rate of the LCDLMs in the classroom, we did not specify a required length of implementation, type of classroom setting, or what other activities beyond those suggested on the worksheet that could be used in the classroom. Therefore, the exact implementation procedure varied between institutions and is described in further detail below. While we recognize that the variability between implementations is a limitation of our study, we also consider this a strength considering that this approach improved ecological validity and more closely mirrors how LCDLMs will be used in different classrooms and settings.

2.2 *Hands-on Implementation Procedure*

For all 16 hands-on implementations of the hydraulic loss or double pipe LCDLMs, students worked in groups of 2–4 in a conventional lecture hall or laboratory setting. Students assembled the kit shown in Fig. 1A or 1B and worked in teams to complete the LCDLM activities outlined in a worksheet, full versions of which are available on our webpage [17]. On the hydraulic loss module worksheet, students were instructed to visually observe, graph, and describe pressure and velocity trends a as function of position in the module, record manometer height data at three different volumetric flowrates and discuss how flowrate affected pressure drop, and observe the effect of tilting one end of the module upwards on the velocity trend. On the double pipe heat exchanger worksheet, students were asked to collect three sets temperature data at varying flow rates or inlet temperature, observe flow patterns, and answer a series of short answer questions related to identifying the system boundary for an energy balance, the areas for fluid flow and heat transfer, and temperatures and geometric parameters used in the energy balance and heat transfer correlations. Implementing instructors reported that students completed the majority of the in-class portion of the worksheet in all but two implementations, where one professor chose not to use the worksheet and the other chose to use about a quarter of it.

2.3 *Virtual Implementation Procedure*

In spring 2020, restrictions on in-person instruction at many universities necessitated the creation of virtual materials for LCDLM implementations and allowed us to study the effectiveness of the LCDLMs outside of the historically utilized interactive, hands-on classroom setting. Due to the variability in instructional format across participating institutions, three broad virtual implementation formats were used: (1) fully asynchronous where students watched videos and completed the worksheet outside of class, (2) partially synchronous where students watched videos or received detailed instruction about the activity in a live class session but completed the worksheet outside of class, or (3) fully synchronous where students watched videos and completed the worksheet in a live class session. Initial comparison of conceptual understanding gains across virtual implementation formats revealed no significant differences between groups for either module; thus, we chose to combine all virtual implementation results. There were 6 fully asynchronous, 2 partially synchronous and 4 fully synchronous virtual implementations for a total of 12 implementations. All students, at minimum, watched a short demonstration video, ~9 and 9.5 min long for the hydraulic loss and double pipe heat exchanger modules, respectively, which was publicly available on YouTube [18]. In the video, a researcher explained the experimental set-up, demonstrated data collection for each qualitative and quantitative worksheet experiment, discussed basic visual observations, and suggested that students complete associated sections of the worksheet, which was assigned in all but three virtual implementations. Finally, for the double pipe module, 74 students in three implementations watched five additional short 2:27–3:06 minute narrated, animated videos focused on a more comprehensive conceptual explanation of each worksheet learning objective, including flow paths of the hot and cold fluid; comparison of fluid flow areas and the heat transfer area; the system boundary for cold fluid in the double pipe heat exchanger; the heat transfer rate equation and the impact of changes to the overall heat transfer coefficient, heat transfer area, and log mean temperature difference; and the impact of changing the mass flow rate and inlet fluid temperatures on the heat transfer rate. Four conceptual videos were also created and available on YouTube for the hydraulic loss module, but no instructors reported using or assigning them. Virtual materials continue to be publicly accessible on our YouTube site [18].

2.4 Pre- and Post-activity Conceptual Assessments

A summary of questions asked on pre- and posttest assessments and the number of responses for each question are shown in Table 1 for the hydraulic loss and double pipe heat exchanger modules.

Full versions of each question and associated answer choices are presented in the Appendix. Multiple choice assessments were administered via the Qualtrics XM platform. A pre-test was taken in class for 82% of hands-on implementations, during synchronous class time for 17% virtual implementations, and outside the class for remaining implementations within 8 days before LCDLM implementation. The posttest was taken in-class for 71% of hands-on implementations, during synchronous class time for 17% of virtual implementations and outside the class for remaining implementations within 12 days after the activity. Each question was related to a learning objective listed on the activity worksheet where question clarity was evaluated by a group of professors and graduate students during assessment development. All the double pipe questions and Questions 3 and 4 for the hydraulic loss module were also evaluated by a small focus group of chemical engineering undergraduate students. For both modules, several questions were repeated on both the pre- and posttest and the posttest contained at least one additional question. Assessments were identical across all virtual hydraulic loss implementations and all double pipe implementations with the exception of Question 1 on the double pipe assessment, which was asked for all hands-on implementations but only one virtual implementation due to a logistical error. For the hands-on hydraulic loss implementations, the questions asked on the pretest were varied each semester so that learning gains could be evaluated for all assessment questions, but the posttest was identical. Individual assessment questions were graded as correct or incorrect, with a score of 0 or 1.

2.5 Data Set and Statistical Analysis

Implementation effectiveness was evaluated for four implementation methods: (1) hands-on implementation of hydraulic loss module; (2) virtual

Table 1. Overview of hydraulic loss (HL) and double pipe (DP) assessment questions and number of responses

	Hands-on		Virtual	
Overview of Question	**Pre-test**	**Posttest**	**Pre-test**	**Posttest**
HL 1a: Select correct graph of velocity vs. distance in pipe	213	213	136	136
HL 1b: Reasoning/explanation for choice in question 1a	213	213	136	136
HL 2a: Select correct graph of pressure vs. distance in pipe	51	213	136	136
HL 2b: Reasoning/explanation for choice in 2a	0	213	0	136
HL 3: Velocity in downward, constant diameter coil	0	213	162	136
HL 4: Possible option to reduce head loss in a straight pipe	213	213	136	136
DP 1: System boundary for heat duty calc. in flat plate exchanger	234	234	25	25
DP 2a: Effect of heat exchanger length on heat duty	234	234	180	180
DP 2b: Reasoning/explanation of choice in Question 2a	234	234	180	180
DP 3: Direction of and driving force for heat transfer	234	234	180	180
DP 4: Duct diameter giving most heat transfer to inset tube	234	234	180	180
DP 5: Direction of transfer and equation for hot-side heat duty	0	234	0	180

Table 2. Implementation and participant details for each study group

Group	Implementations	Students	Average class size	Data collection period
Hands-on Hydraulic Loss	10	213	27	Fall 2019–Fall 2020
Virtual Hydraulic Loss	6	136	23	Spring 2020–Fall 2020
Hands-on Double Pipe	6	234	39	Fall 2019–Spring 2020
Virtual Double Pipe	6	180	30	Spring 2020

implementation of the hydraulic loss module; (3) hands-on implementation of the double pipe heat exchanger module and (4) virtual implementation of the double pipe heat exchanger module. Data was collected from consenting second through fourth year students in chemical and mechanical engineering courses from fall 2019 – fall 2020. The number of implementations and students, average class size, and data collection period for each treatment group is summarized in Table 2.

All statistical analysis of pre- and posttest data was completed in IBM® SPSS® Statistics 27 using data from students who consented and completed both assessments. Overall pre- and posttest scores were compared using paired samples t-tests and Hedges' g effect size. Independent samples t-tests were used for between-group comparison of the average score change, defined as the posttest score minus the pre-test score, and ANOVA or Welch's ANOVA were used to compare score changes between implementations within each group. All differences were considered statistically significant at $p < 0.05$. For score comparison of individual assessment questions, McNemar's test, used in place of paired samples t-tests due to the binary nature of assessment grading, was used to determine if a significantly higher number of students changed their assessment response from incorrect to correct than from correct to incorrect, an indication that the activity had a positive effect on conceptual understanding.

3. Results

3.1 Effect of Implementation Format on Overall Assessment Performance

Comparison of the average overall score change in hands-on and virtual groups indicates that implementation format did not have a significant impact on conceptual understanding for either the hydraulic loss or double pipe module groups. Fig. 2A and 2B show the posttest score was significantly higher than the pre-test score for all treatment groups ($p < 0.05$), indicating students benefited from all LCDLM activities. For the hydraulic loss module, moderate ($g = 0.61$) and large effect sizes ($g = 0.80$) were observed for the virtual group and hands-on group, respectively, indicating a highly effective intervention. The score changes were 31.2% for hands-on and 24.0% for virtual groups, with no statistical difference ($p = 0.1$) for the hydraulic loss module, indicating conceptual effectiveness of the LCDLM implementations was independent of implementation format. For the double pipe a small effect size ($g = 0.34$) was observed for both groups and smaller changes of 8.2% and 9.2%, with no statistical difference ($p = 0.69$), were observed for the hands-on and virtual groups, respectively, again

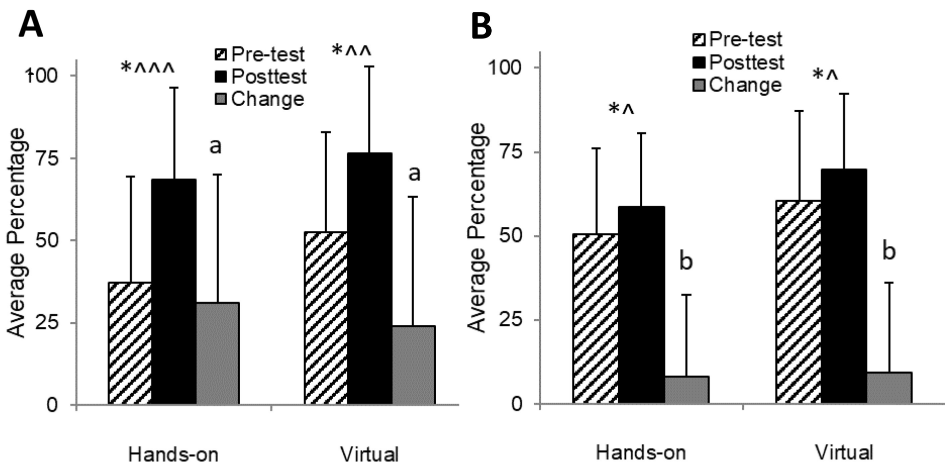

Fig. 2. Average pre- and posttest assessment scores and average score change for (A) hydraulic loss module and (B) double pipe heat exchanger hands-on and virtual groups. Score change bars sharing a letter are statistically similar at p > 0.05. * represents significant within-group score increases and ^, ^^ & ^^^ indicate small, moderate, and large within-group effect sizes.

supporting the conclusion that the conceptual effectiveness of the LCDLM implementations was independent of implementation format. Comparison of results for the hydraulic loss versus the double pipe heat exchanger module will be discussed later in section 3.3.

In summary, no significant differences between learning gains between hands-on and virtual demonstrations were observed for either LCDLM.

3.2 Effect of Implementation Format on Performance on Individual Assessment Questions

Comparing student performance for both modules on individual assessment questions indicates both implementation formats supported increased understanding of the same individual concepts. For the hydraulic loss module, statistically significant improvements were observed for four of five repeated questions for the hands-on group and all questions for the virtual group, as shown in Fig. 3. The largest significant increases ($p < 0.0001$) for both groups occurred on questions 1a, 1b, and 2a, with 25–28% and 48–59% increases in the percentage of students answering each question correctly on the posttest compared to the pre-test for the virtual and hands-on groups, respectively. At least 78% of students answered questions 1a–2a correctly on the posttest in both groups, indicating both implementation methods were highly effective for promoting understanding of the velocity and pressure profiles in a constant diameter pipe, both of which directly are visually observable during the hands-on experiment and virtual demonstration. The hands-on group also showed a statistically significant ($p < 0.01$), but smaller 15% improvement in the percent of students who correctly answered Question 3, on understanding that velocity does not change in a downward sloping coil of constant diameter. This showed transference of understanding from an experiment in the hands-on or video implementations about the effect of gravity on velocity from a simple straight pipe geometry to a more complex coiled geometry. Finally, the hands-on group did not improve and the virtual group showed only a marginally significant increase of 11% ($p = 0.049$) on Question 4, where students determined whether increasing the velocity, increasing or decreasing increasing the pipe diameter, or decreasing the relative roughness would decrease head loss, only the first of which was observed during experimentation.

For the double pipe module, hands-on and virtual implementations also fostered similar improvement on individual assessment questions. As shown in Fig. 4, a statistically significant effect for both groups was observed for question 1, which shows improvements from 16–20% of the students on the pre-test having a correct understanding of the system boundary used to calculate the hot-side heat duty in a simple two-dimensional pictorial display of a flat plate exchanger, to an average of 27–52% on the posttest. The concept was directly addressed on the associated worksheet via a short answer discussion question. Students in the virtual group also improved significantly on question 2a ($p = 0.01$) with a nearly significant effect on question 2b ($p = 0.053$), where they were asked to identify whether a shorter or longer heat exchanger would have a higher heat transfer rate and the reasoning for their choice. This was not addressed on the worksheet beyond showing the equation for the heat transfer rate and asking students to describe the area for heat transfer, but was addressed in a conceptual video watched by the approximately 40% of students in the virtual implementation group who were instructed to do so. A significant McNemar's test result ($p < 0.01$) was observed for the group of 74 students participating in virtual implementations who watched the conceptual video which directly addressed the relationship between

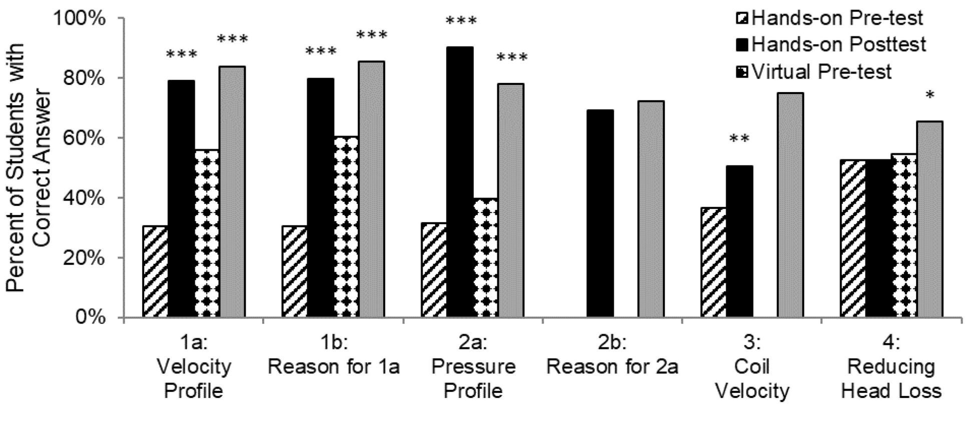

Fig. 3. Percentage of students with correct pre- and posttest answers on individual hydraulic loss assessment questions for hands-on and virtual groups. *, **, and *** indicate statistically significant McNemar's test result at $p < 0.05$, $p < 0.01$, and $p < 0.0001$, respectively, for paired pre- and posttest responses.

exchanger length and heat transfer rate, but not for the group of 106 virtual students who did not. This indicates that this video was useful for improving understanding of the basic heat transfer principle addressed in question 2, that increased surface area for heat transfer increases the heat transfer rate, for the 31% of students who answered incorrectly on the pre-test and supports the use of conceptual videos even in a hands-on setting as supporting material. For the remaining two repeated assessment questions, nonsignificant improvement was observed for both groups. Question 3 required students to identify the direction of and driving force for heat transfer, i.e., an energy or temperature difference. According to Prince et al. [19], students tend to misinterpret the relationship between temperature and energy, believing that temperature is a direct indicator of an object's energy. Although 73% of students demonstrated they already understood this concept on the pre-test, this misconception, which was not directly addressed during the LCDLM activities, may have caused the remaining 19–23% of students to still answer question 3 incorrectly on the posttest. Question 4 required students to first understand the relationship between annular duct diameter and velocity, then correctly understand the effect of velocity, and hence Reynolds number, on the heat transfer rate. Though students observed the relationship between velocity and heat transfer rate in the hands-on or demonstrated experiment and this was discussed in a conceptual video, the relationship between outer annular diameter and velocity was not covered which could have resulted in poor understanding. Finally, students demonstrated a high level of understanding on question 5, with 76–79% answering correctly on the posttest, where they identified the correct equation for the heat duty of the hot fluid. This was directly related to a worksheet question where students were asked to write the same equation.

In summary, although the magnitude of learning gains varied between assessment questions, consistent improvement trends were observed between hands-on and virtual implementations for both hydraulic loss and double pipe modules, with the exception of question 2A on the double pipe assessment where only students in the virtual group significantly improved, suggesting that students learned similar information in both formats.

3.3 Effect of Module on Overall Assessment Performance and Performance on Individual Questions

Comparison of score changes indicates the hydraulic loss module promoted significantly greater learning gains than the double pipe heat exchanger for both hands-on and virtual implementations. As shown previously in Fig. 2 in section 3.1, for hands-on implementations, the average score change for the hydraulic loss module, 31.2%, was 3.8 times larger than the 8.2% change observed for the double pipe module. This difference was statistically significant ($p < 0.0001$) with a moderate effect size ($g = 0.72$). Similarly, for virtual implementations, the 24% change for the hydraulic loss group was 2.6 times and significantly larger ($p < 0.001$) with a small effect size ($g = 0.45$) than the 9.2% change for the double pipe group. From the overall assessment results, it should be noted that the average posttest scores of 68.4% for hands-on and 76.6% for virtual hydraulic loss module implementations were significantly higher ($p < 0.05$) when compared to scores of 58.6% for hands-on and 69.7% for virtual double pipe implementations. Regarding individual assessment questions, students improved on 4 of 5 and all repeated questions with 40 and 26% average increases in the numbers of students answering correctly, for hands-on and virtual hydraulic loss implementations, respectively. For the hands-on and virtual double pipe implementations, students still improved overall,

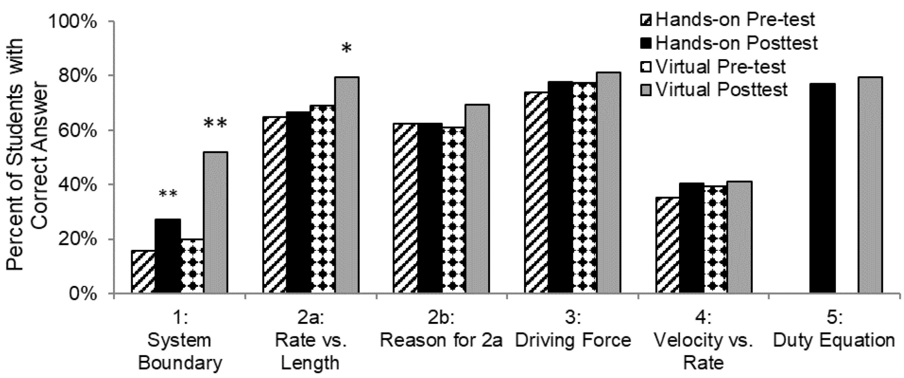

Fig. 4. Percentage of students with correct pre- and posttest answers on individual double pipe assessment questions for hands-on and virtual groups. * and ** indicate statistically significant McNemar's test result at p < 0.05 and p < 0.01, respectively, for paired pre- and posttest responses.

Table 3. Scoring Criteria for Relatedness Score and Assessment Questions which met each criterion

Criteria	Example of items which met criteria	Assessment questions which met criterion
Students visually observed assessed concept during experiment.	Pressure and velocity in hydraulic loss; flow patterns in heat exchanger.	Hydraulic loss: #1a, 1b, 2a Double pipe: N/A
Students measured experimental data directly related to assessed concept, or could infer information about concepts from measured quantities.	Pressure in hydraulic loss; heat transfer rate vs. velocity (from temperature, flow rate measurements), head loss vs. velocity (from manometer height and flowrate measurements).	Hydraulic loss: #2a, 4 Double pipe: #4
Worksheet included conceptual discussion question(s) directly related to concept; questions where students were only asked to write an equation excluded.	Velocity and pressure in hydraulic loss, system boundary in heat exchanger.	Hydraulic loss: #1a, 1b, 2a, 3 Double pipe: #1

but only on 1 of 5 and 2 of 5 questions with average improvements of 4.5 and 11.3%, respectively. The significantly higher gains in overall conceptual understanding, higher posttest scores, and the greater improvement on individual questions support the conclusion that the current hydraulic loss module activity promotes greater learning of concepts. However, the varying magnitude of learning gains for individual questions for both modules and the observation that students performed better on questions addressing concepts directly observed during experimentation or addressed on the worksheets suggests the need to consider how well-aligned each assessment is with the activities. Activity and assessment alignment is quantified and the impact of alignment on student learning is explored in further detail below.

3.4 Relationship between Student Improvement and Alignment

To quantify the alignment between each assessment question and the LCDLM activity and explore how alignment relates to student performance, we assigned each hydraulic loss and double pipe assessment question a relatedness score. Scores ranging from 0–3 were assigned to each question based on the criteria in Table 3 with one point ascribed for meeting each of the three criteria. For the second criterion, a full point was added if students measured data directly related to the concept assessed, for example, using manometer height measurements to identify pressure trends, and 0.5 of a point was added when students measured quantities that could be used more indirectly to infer information about the assessed concept, such as using temperature and flowrate measurements to identify the relationship between heat transfer rate and flowrate.

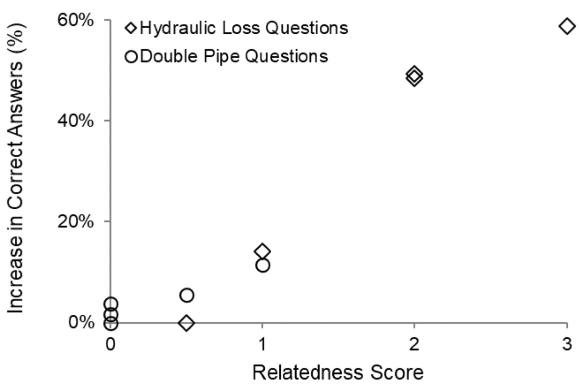

Fig. 5. Percentage increase in correct answers on posttests compared to pre-tests versus question relatedness score for hands-on hydraulic loss and double pipe implementations.

As shown in Fig. 5, a larger increase in percentage of students who answered assessment questions correctly occurred for questions with a higher relatedness score for hands-on implementations, evidenced by the 0–14% increases in the percent of correct answers for questions with a relatedness score of 0–1 and larger 48–59% increases for questions with a relatedness scores of 2 or 3. Also, important to note in Fig. 5 is that the double pipe assessment questions had an average relatedness score of only 0.3 compared to higher average relatedness score of 1.7 for the hydraulic loss module. This supports an argument that the hydraulic loss module was more effective than the double pipe module due to the inherently more visual nature of the physical phenomena in the experimental activities and the focus of the worksheet and assessment questions on those phenomena.

4. Discussion

4.1 Effect of Implementation Format on Student Learning

Results presented in sections 3.1 and 3.2 show that hands-on and virtual demonstration formats were equally effective for promoting both similar overall learning gains and improvements in understanding of similar concepts. Existing literature on the effectiveness of hands-on experimentation and in-person demonstration shows mixed findings. Statistically similar 16–34% gains in understanding, assessed through a conceptual test on reaction chemistry were observed for students who completed a hands-on chemistry experiment or watched an in-person, instructor-led demonstration in a study by McKee et al. [20]. Glasson also reports similar scores on a declarative knowledge assessment taken by high-school physical science students after hands-on experiments or teacher demonstrations on simple mechanics, although students who performed hands-on experiments outperformed those who watched a demonstration by 11% when asked to solve more complex problems [21]. Logar and Savec found high-school chemistry students who watched a teacher's lecture demonstration performed significantly better on conceptual posttests than students who completed an experiment in pairs [22]. In contrast, Harty and Al-Faleh found high school chemistry students who completed hands-on experiments in groups performed significantly better than students who watched instructor demonstrations in a large lecture, with 6% and 11% higher scores on conceptual assessments administered immediately after and one week after the activities, respectively [23]. The lack of consensus in the literature regarding the relative effectiveness of hands-on experimentation compared to in-person demonstration suggests a dependence on the structure and content of the activities.

Although hands-on LCDLM implementations facilitate increased interaction with peers, shown in several studies to be beneficial for learning compared to other modes of active engagement [3–5], features of the hands-on environment may have influenced effectiveness. Suboptimal group dynamics may decrease the effectiveness of collaborative learning as suggested by Haller et al. [24] who describe challenges commonly observed during group work, where some students always rely on other group members to explain concepts or dismiss another student's opinion without merit. These findings are supported in a study by Theobald et al. [25], where students who reported a highly dominant personality in their group or that they did not feel comfortable in their group scored lower on a conceptual posttest than students who did not report these issues. Further, not all students engage equally in collaborative activities, as shown in a study by James and Willoughby on the behaviors occurring during peer discussion in a clicker question activity, where 7% of students passively deferred to a peer's answer without rationale or did not engage in conversation at all [26]. Thus, the group interaction element of the hands-on activity may not have been beneficial for all students due to differences in group behavior and engagement of individual students. Additionally, cognitive load on students during activities must be considered. Choi et al. [27] argue that the physical learning environment significantly affects learning through an influence on cognitive load; for example, auditory and visual distractions can increase the load on students' limited working memory, required for cognitive processing, leading to decreased learning. In contrast, video-based learning may optimize working memory load as students are able to manage load by pausing or rewinding material and instructors can limit extraneous load, arising from content-irrelevant details and distractions, by editing video materials [12]. Taken together, the hypothesized variability of group dynamics and the influence of the physical learning environment on the effectiveness of the hands-on activity may explain the statistically insignificant p-value between the virtual and hands-on overall learning gains observed, even though the hands-on activity promoted a higher level of engagement by lowering the barriers to peer interaction.

Supporting evidence that the learning environment impacted the effectiveness of hands-on implementations is demonstrated through within-group ANOVA analyses comparing the average score change for each implementation. Table 4 shows the score change was significantly different for hydraulic loss ($p = 4.1 \times 10^{-7}$) and double pipe ($p = 0.025$) hands-on implementations, but that there were insignificant variations in both virtual groups ($p > 0.05$).

Although factors including the experience level of students, implementation length, and worksheet usage varied in both virtual and hands-on formats, only hands-on implementations showed a significant variation in effectiveness. Therefore, we hypothesize that the increased variability observed for hands-on implementations is the result of fac-

Table 4. Results from ANOVA on score change between individual implementations for each treatment group

Method	Module	Lowest Change in Average Score	Highest Change in Average Score	p-value from ANOVA with implementation as grouping variable
Hands-on	Hydraulic Loss	–5%	62.5%	4.1×10^{-7}
	Double Pipe	1.7%	18.1%	0.025
Virtual	Hydraulic Loss	10.7%	45.1%	0.11
	Double Pipe	4.6%	15.8%	0.57

tors unique to the hands-on experience including the amount of professor guidance, management of the physical learning environment, group dynamics, and the accuracy of student experimental observations. Students in virtual groups received an accurate and homogeneous presentation and explanation of the experimental portion of the LCDLM activity, whereas experimental results and the degree of explanation varied in hands-on implementations. Further, the importance of instructor guidance during hands-on activities is supported in recent literature which opposes pure discovery-based learning, where students are minimally guided by instructors and are expected to discover and construct information independently. Mayer [28] and Kirschner et al. [29] both argue that guided-discovery activities where structure is provided to help students recognize and organize relevant information, are more effective than pure discovery-based activities and can lower demand on the learner's working memory. Although worksheets were provided to facilitate a guided and structured experience for the LCDLM activities, our results show student learning gains in hands-on groups still varied between implementations, suggesting that instructors must work to ensure a homogeneous learning experience, guide students, and correct misconceptions. In summary, two conclusions can be drawn from the comparison of overall learning gains for hands-on and virtual implementations: first, no significant differences were observed in overall learning gains for virtual versus hands-on implementations which supports the continued use of virtual demonstration materials in online courses or at resource-limited institutions where hands-on learning is challenging; and second, significant variability between implementations occurred during hands-on but not virtual implementations, supporting the importance of managing the hands-on learning environment.

4.2 Effect of Module and Activity Alignment on Learning Gains

Results presented in sections 3.3 and 3.4 show that students learning gains were significantly greater for hydraulic loss implementations than for double pipe heat exchanger implementations. We have demonstrated that this discrepancy is likely caused better alignment between the concepts seen, measured, and discussed during the LCDLM activity and assessed concepts for the hydraulic loss module. Concepts emphasized on the hydraulic loss assessment, including velocity and pressure trends, were both highly observable and highlighted on the worksheet, providing students several opportunities to directly observe and reflect on those concepts prior to the posttest. In contrast, many of the questions on the double pipe assessment focused the heat transfer rate in the LCDLM, which is difficult for students to quantify based on observation alone because of its dependence on multiple factors including temperature driving force, heat capacity and flow rate, and because students need to calculate the rate before comparing results from their experiments. Further, much of the double pipe worksheet was focused on asking students to write equations relevant to heat transfer calculations or consider how to use their experimental data to calculate terms in equations, rather than consider the implications of their experimental results. Evaluating each assessment question based on the relatedness score demonstrates the importance of alignment between assessed concepts and the hands-on activity; the LCDLM activities prove most beneficial for improving understanding of experimentally observable, highly emphasized concepts.

The importance of hands-on activity and assessment alignment is also demonstrated in prior studies. Cirenza et al. developed a series of heat-transfer focused workshops wherein students conducted a physical experiment addressing important heat transfer concepts then completed a series of reflective questions related to the activity [11].Their findings are in support of the premise that students who complete hands-on workshops will significantly outperform those who receive traditional lecture on questions directly related to concepts explored during more than one workshop activity but not on more general quiz and exam problems. Similarly, Schwichow et al. [10] show students perform significantly better on a hands-on assessment task directly related to the intervention activity, focused on designing and interpreting controlled experiments, than an assessment task focused on the same governing concepts with a different physical application. Both studies suggest hands-on activities are most helpful for teaching task-specific knowledge, aligning with our results showing improved understanding of highly emphasized concepts. These results stress the importance of formulating activities to include experiential, visual, tangible, and reflective aspects to make learning of important concepts effective through short hands-on or virtual activities. Moreover, assessments need to coincide or align with these aspects to demonstrate activity efficacy.

5. Conclusions, Implications, and Future Work

Through comparison of conceptual assessment results collected at 15 universities during hands-on and virtual demonstration implementations of two

LCDLMs, two important conclusions can be drawn. First, hands-on and virtual demonstration implementation methods as implemented promote statistically similar, significant positive overall gains in student performance, offering strong evidence that both methods are effective for teaching fluid mechanics and heat transfer concepts. This supports the continued use of virtual materials beyond applications necessitated by the COVID-19 pandemic for resource-limited institutions, online programs, distance education where hands-on learning is impractical, and more generally, providing additional depth after hands-on experiences. Virtual materials will continue to be publicly available for extended use. Further, we observed significant variability in student performance between implementations for hands-on but not virtual implementations, suggesting that carefully constructed virtual demonstrations increased the homogeneity of student learning experiences. Second, we observed a significant impact of the module employed during implementation on overall learning gains. Gains were significantly higher for the hydraulic loss LCDLM, focused on fluid mechanics phenomena, than for the double pipe heat exchanger LCDLM, focused on heat transfer. Through comparison of the assessments used to measure student learning for both modules, we found this difference was likely caused by robust alignment of the hydraulic loss conceptual assessment questions with the LCDLM experiments and worksheet, as well as the inherently more visual, observable nature of fluid mechanics concepts such as pressure and velocity compared to heat transfer concepts. Broadly, our results indicate a critical need to carefully design hands-on learning and virtual learning experiences so students have ample opportunity to observe, discuss, and reflect on concepts emphasized in learning assessments, and to consider the quality of the learning environment during these experiences.

Based on these conclusions, we plan to assess several aspects of LCDLM implementations in more detail. First, we are restructuring the double pipe LCDLM activities so visual aspects, such as areas for heat transfer and fluid flow and fluid flow patterns are emphasized and assessed and plan to strategically leverage the worksheet and encourage instructor intervention to help students easily make connections between experimentally measured parameters and more complex concepts such as the heat transfer rate. We hypothesize that these changes will improve the effectiveness of the double pipe LCDLM activity so similar conceptual gains as the hydraulic loss activity are observed. Next, based on the results of varying effectiveness of hands-on implementations on conceptual understanding gains for both modules, we plan to further characterize aspects of the classroom environment and implementation procedure that lead to effective learning and develop best-practice guidelines, allowing strategic management of hands-on learning experiences to maximize student learning.

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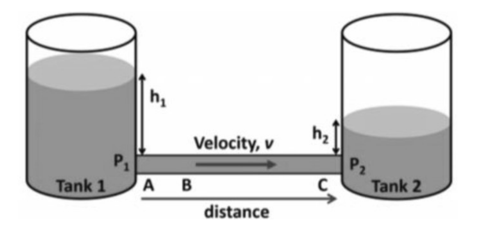
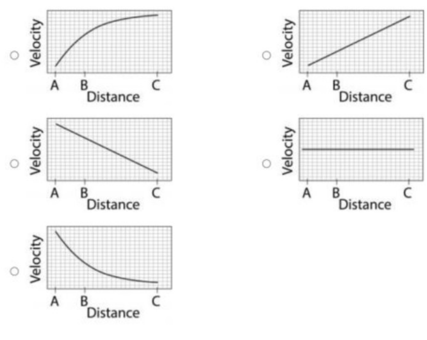
Appendix: Hydraulic loss (HL) and double pipe heat exchanger (DP) assessment questions and answer options

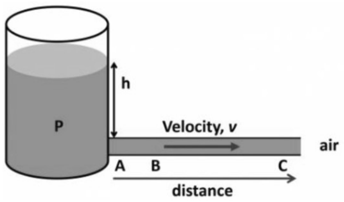
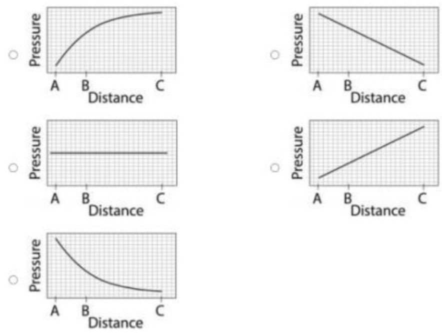
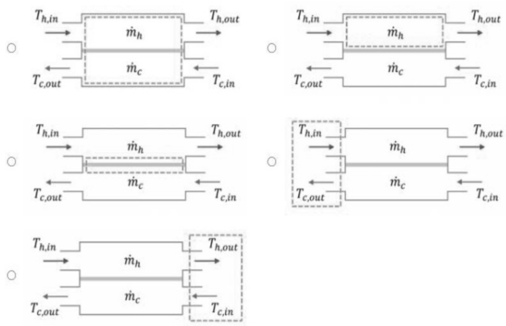
<table>
<tr><th>Question</th><th>Question Text and/or Image</th><th>Answer options</th></tr>
<tr><td>HL 1a</td><td>

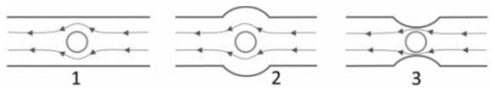


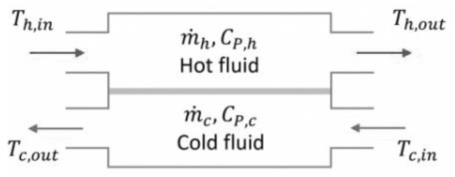
Water flows through a pipe from Tank 1 to Tank 2. The water level in each tank is indicated at an instance in time. Assuming steady-state flow, select the correct graph of velocity versus distance down the pipe.</td><td>



</td></tr>
<tr><td>HL 1b</td><td>Because...</td><td>(a) The velocity increases near the pipe entrance because of the pressure gradient, but accelerates slowly at the pipe exit because of friction.
(b) The velocity increases down the pipe because of the pressure gradient.
(c) The force of friction reduces the velocity of the liquid.
(d) The cross sectional area is constant, thus the velocity is constant to conserve mass.
(e) The velocity decreases near the pipe entrance due to friction and then decelerates since friction is reduced when it moves slower.</td></tr>
</table>

HL 2a	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? 	
HL 2b	Because. . .	(a) Frictional losses within the pipe will decrease velocity nonlinearly, so pressure must also decrease nonlinearly. (b) Frictional losses within the pipe will decrease pressure linearly. (c) The fluid is not accelerating, so the pressure must be constant. (d) Frictional losses within the pipe will increase pressure The fluid speeds up through the pipe, so pressure must decrease.
HL 3	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? 	(a) The velocity will increase because the fluid is flowing downwards and is driven by gravity. (b) The velocity will remain constant because the pipe has a constant diameter and mass must be conserved. (c) The velocity will decrease because of friction on the pipe walls. (d) The velocity will remain constant because the increase in velocity due to gravitational forces is counterbalanced by the decrease due to friction.
HL 4	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.	(a) Increase the fluid velocity. (b) Decrease the pipe diameter. (c) Increase the pipe diameter. (d) Use a piping material with a higher relative roughness to decrease the friction factor.
DP 1	Below is the schematic of a simple heat exchanger with different system boundaries (green dashed box). If you want to determine the rate of heat transfer, Q, from the hot fluid to the cold fluid, which would you pick as the system to analyze?	
DP 2a	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?	(a) Longer one. (b) Shorter one. (c) Same in both heat exchangers.
DP 2b	Because. . ..	(a) Heat transfer does not depend on the length of the heat exchangers. (b) Having a constant mass flow rate and heat capacity should yield the same heat transfer rate. (c) The longer tube length offers a higher surface area for heat transfer. (d) The longer tube length provides a longer residence time. (e) Shorter tube length offers higher velocity through the tube which offers higher heat transfer rates.

<table>
<tr><td>DP 3</td><td>Consider two systems filled with air: system A at a uniform temperature T_A and system B at another uniform temperature T_B where $T_A > T_B$. Both systems have the same volume and pressure. Let the two systems be brought into contact by a heat conductive surface and be thermally insulated from their surroundings. Energy will flow from:</td><td>(a) System A to system B by energy difference.
(b) System B to system A by energy difference.
(c) System A to system B by temperature difference.
(d) System B to system A by temperature difference.</td></tr>
<tr><td>DP 4</td><td>

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?</td><td>(a) Setup (2) because it will provide the lowest fluid velocity passing over the duct.
(b) Setup (1) because it offers a balance between velocity and pressure drop passing over the duct.
(c) Setup (3) because it will offer the highest possible fluid velocity passing over the duct.
(d) All setups will give the same rate of heat transfer because flow rate is the same in each case.</td></tr>
<tr><td>DP 5</td><td>The following figure represents a block diagram of a heat exchanger. Which of the following statements are correct?

</td><td>(a) The cold fluid picks up heat:
$\dot{m}_c C_{p,c}(T_{h,in} - T_{c,in})$
(b) The hot fluid gives up heat:
$\dot{m}_h C_{p,h}(T_{h,in} - T_{c,in})$
(c) The cold fluid picks up heat:
$\dot{m}_c C_{p,h}(T_{c,out} - T_{h,out})$
(d) The hot fluid gives up heat:
$\dot{m}_h C_{p,h}(T_{h,in} - T_{h,out})$</td></tr>
</table>

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