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Design, Fabrication, Testing, and Implementation of a Low-Cost Venturi Meter for Hands-on Active Learning*

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In engineering education, conceptual understanding of the subject matter is as important as the attainment of practical skills. Therefore, teaching methodology should be designed in such a way that it enhances student conceptual understanding. To enhance conceptual understanding of fluid flow measurement, in this study, we report on the development of a low-cost, small-sized, reproducible, highly visual venturi meter module for active learning. With this module, students can conduct fluid flow experiments in their classroom or lab setting to learn the fundamental principles behind the venturi meter. Quantitative measurements of flow rates and associated parameters with the module reveal its usefulness for demonstrating fluid flow physics, while worksheet-guided studies promote student engagement and conceptual understanding. Results of pretest, posttest, and motivational survey assessments show that the module and associated activities improve conceptual understanding, result in a surge in confidence, and reinforce the desire to participate. Therefore, based on the findings, the modules developed can be used to enhance student understanding in fluid mechanics courses.

Keywords: venturi meter; hands-on experiments; fluid mechanics; flow measurement; active learning

1. Introduction

Active learning is often synonymized as learning by doing, which differs from traditional learning where students receive information through lectures. Under the active learning premise, an instructional method engages students in meaningful learning activities [1]. Thus, student activity and meaningful engagement in the learning process are the core elements of active learning [2]. It has been found that active learning increases student performance in science, technology, engineering, and mathematics (STEM) education [3].

Students are more engaged when active learning through hands-on experiments is employed because it requires them to learn by doing rather than solely through the passive reception of information. By carrying on an investigation on the influence of hands-on activities, which included experimentation, work with microscopes, dissection, and classification of creatures, Holstermann et al. found a positive effect on student interest [4]. In addition, improvement in both student participation (91.7% of the students preferred the activity-oriented learning method) and performance (17.6% increase in mean score) were observed due to the incorporation of a hands-on approach in mathematics and basic science class [5]. Moreover, it has been observed that a carefully designed hands-on learning project can complement classroom lectures and contribute towards the development of student critical thinking and group work skills [6]. Demonstration

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models allow students to quickly grasp theory as the addition of demonstration models to the curriculum significantly improves student learning outcomes [7]. Therefore, the introduction of hands-on experiments in chemical and mechanical engineering undergraduate classrooms is very important to help explain complex subject matter in heat transfer and fluid mechanics, which is the focus in this paper.

To create better understanding of relationships between theory and physical experiment, several universities have revised their undergraduate engineering programs [8–10]. For example, Worcester Polytechnique Institute has re-designed aerodynamics, fluid mechanics, and heat transfer classes by adjoining a multimedia classroom with experimental laboratory and computational facilities to demonstrate experimental apparatuses directly in the class during a lecture [8]. Although these apparatuses offer real-time quantitative data measurements, analysis, and concurrent comparison with the developed theory, this integrated classroom approach requires specially designed learning spaces and costly equipment. To address this challenge, carefully designed but affordable desktop learning modules (DLMs) could be an excellent alternative. By replicating industrial heat transfer and fluid mechanics equipment, our group has developed several miniaturized, highly visual, and low-cost DLMs for heat transfer and fluid mechanics courses [11]. With these modules, students can conduct experiments in their classroom or lab setting to learn fundamental principles behind several industrial pieces of equipment. These DLMs are positively received by students and educators [12] and most importantly, they are highly effective for improving student conceptual understanding of fluid flow physics, fluid energy transformation, thermal energy transfer, and exchange of energy between fluids [13–15]. Although several DLMs such as a hydraulic loss measurement apparatus, venturi meter, double pipe heat exchanger, and shell-and-tube heat exchanger have been developed, the focus of this paper will be limited only to the venturi meter.

The venturi meter is an accurate, reliable, low maintenance, and widely used flow measurement device that uses differential pressure to measure volumetric flow rates. However, the phenomena of fluid continuity and energy transformation occurring in a venturi meter are complex. Therefore, there are persistent misconceptions revolving around venturi meter principles for flow measurements. For example, most students think that the pressure should rise linearly as the fluid approaches the throat through the gradually decreasing diameter because fluid is being "squeezed" [16] which is opposite to the ongoing physical phenomena. In a traditional classroom setting, it is difficult to provide a long-term remedy to this misconception. Therefore, the target of this paper is to provide an effective hands-on way to teach the fluid flow measurement principles used in the venturi meter. We expect that introduction of venturi meter modules in the undergraduate classroom will provide a long-lasting solution by creating a mental image of the pressure distribution and at the same time, make the learning environment more effective, motivational, and experiential.

To manufacture the venturi meter module, we previously used vacuum forming of plastic sheets around a 3-D printed mold, and then assembled the formed structures and added pumps, valves, and other accessories [14]. Although vacuum forming offered several advantages such as simple and quick mass production at low cost, it frequently produced inconsistent units. Moreover, the durability of those vacuum-formed modules was low because of the thin polyethylene sheets which could easily crack under stress or when get dropped from a desk. In this paper, we report on the design, fabrication, testing, and implementation of a next-generation injection-molded venturi meter module for which we have overcome the problems associated with the earlier vacuum-formed version. The current manufacturing approach allows mass production with high dimensional consistency and fulfills several other requirements including low cost, user friendliness, safety, durability, flow visibility, and flexibility which are essential for widespread and successful adoption [14]. This mass production capability lowers the expense enough to allow every student to have their set-up to explore and learn engineering concepts in ways that are more motivating and lead to deeper understanding. The outcome of the last couple of implementations [17–21] has further strengthened this belief and suggests success for widespread propagation and dissemination of this philosophy throughout the nation and across the world. This paper addresses four primary research questions (RQ):

RQ1. Does the performance of new venturi meter module mimic the industrial scale counterpart with respect to discharge coefficient and pressure recovery?

RQ2. Does the module and associated classroom activity improve student conceptual understanding significantly, i.e., are there significant differences between pre- and posttest scores?

RQ3. Does the venturi DLM reduce the gender gap in the engineering classroom, i.e., to what extent the performance of female students differs male students before and after the DLM activity?

RQ4. Do students believe that use of the DLM is helpful for achieving gains in their own conceptual understanding and classroom engagement?

2. Methods

2.1 Venturi Meter Specifications and Construction

For this study, the venturi meter geometry was designed and specified by using the computer-aided design (CAD) software, SolidWorks$^{\text{TM}}$. The inlet and outlet diameters of the venturi meter are 12.7 mm, while the throat diameter is 4.06 mm. The length of the converging section is 23.3 mm with a converging angle of 10.5° and the length of the diverging section is 70.6 mm with a diverging angle of 3.5°. These angles of convergent and divergent sections conform to industry standards. Detailed specifications of the venturi meter are shown in Fig. 1. Although three manometers at the inlet, throat, and outlet are enough for measurement of pressure drop in the converging section and pressure recovery in the diverging section, we have used five manometers (as shown in Fig. 1) to visualize the nonlinear distribution of pressure with changing diameters. The extra two manometers are placed 11.65 mm and 35.3 mm upstream and downstream of the venturi throat, respectively.

The CAD files were sent to a company to machine the molds and produce the injection molded parts using polycarbonate plastics, which significantly speeds up the manufacturing process. The venturi DLM cartridge was constructed from two mirror-image halves as shown in Fig. 2a. To ensure dimensional consistency, two polycarbonate halves were assembled via robotically assisted application of UV-curable adhesive. All hardware assembly was done by undergraduate students working together in a team under the supervision of an experienced student. The complete experimental set-up (as shown in Fig. 2b) was used for pressure drop, energy transition, and energy recovery experiments.

Besides the DLM cartridge, the complete setup requires several auxiliary elements as shown in Fig. 2c. The complete setup of the venturi meter includes one venturi cartridge (Fig. 2a), one 5/8-inch 90° elbow and straight adapter for the venturi inlet (Fig. 2c(i)), one 5/8-inch 90° elbow with an orifice plate at the venturi outlet (Fig. 2c(ii)), one universal stand (2 legs) to hold the cartridge (Fig. 2c(iii)), one pump (centrifugal water-feature) assembly to maintain the water flow (Fig. 2c(iv)), one rechargeable NiMH 9V (280 mAh) battery to power the pump (Fig. 2c(v)), two 1-liter beakers which work as supply and delivery tanks (Fig. 2c(vi)), one tray to contain spills (Fig. 2c(vii)), and one 9V battery charger (Fig. 2c(viii)). The orifice plate at the venturi outlet is used to avoid air ingestion at throat by providing additional pressure drop. The pump is placed in a 1-liter (inlet) beaker and the module is connected to the pump via Tygon® tubing and elbows fittings. The pump can produce flows of up to 4.0 L/min with a head of 3.0 m in this arrangement when powered by one rechargeable NiMH 12

V battery. Most of the venturi kit components such as pumps, beakers, and fittings, are off-the-shelf items, which ensure easy replacement if components are misplaced or broken during classroom use/handling. The stands were laser cut from acrylic material. In addition, all components are detachable from the setup which ensures easy packaging and transport. Although pumps, battery, and battery holders are off-the-shelf components, to connect the battery holder to the pump, the pump assembly requires soldering and insulation with heat-shrink tubing. The total cost to produce the venturi DLM cartridge and auxiliary kit components is still very low, approximately $90 per setup when producing around 400 units. This cost can be further reduced through larger-scale production.

2.2 Venturi Meter Performance

The venturi meter as shown in Fig. 2(b) was used to collect all fluid flow data reported in this paper. The data are separated into two groups: research group

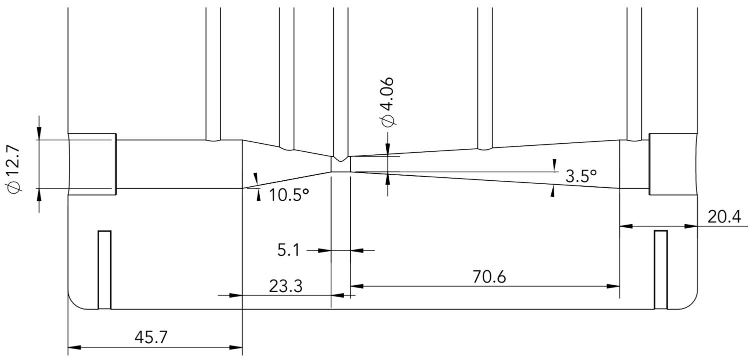

Fig. 1. CAD drawing of the venturi meter (front view). The dimensions are in millimeters.

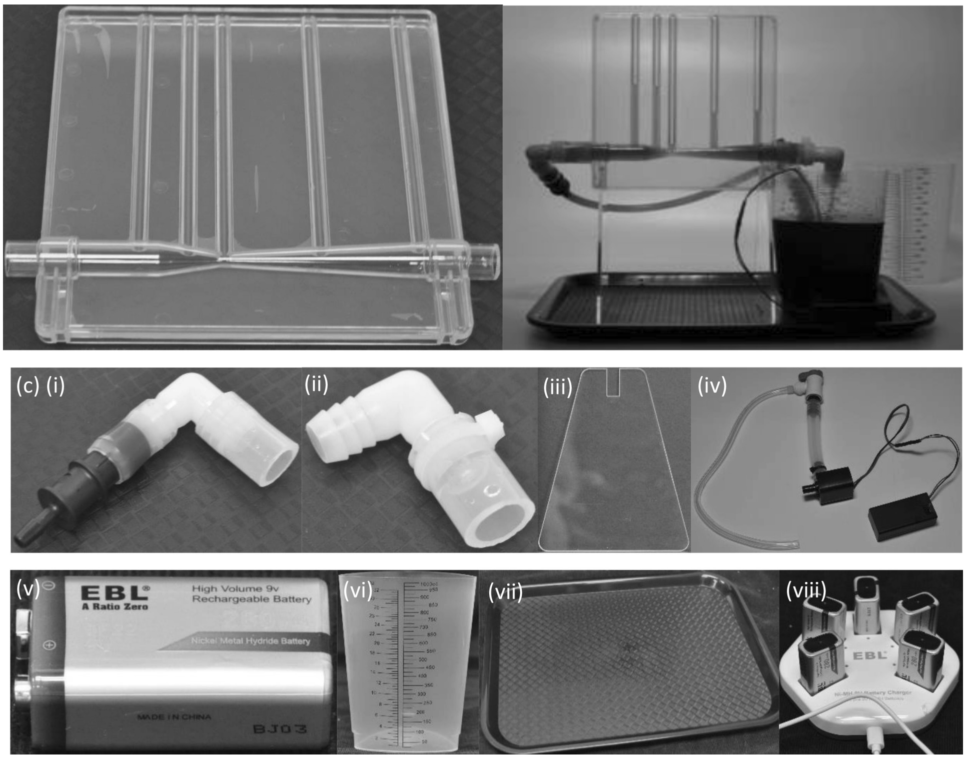

Fig. 2. (a) Venturi meter DLM cartridge, (b) complete experimental setup for flow rate and pressure recovery measurement, and (c) accessories: (i) 5/8-inch 90° elbow and straight adapter (for venturi inlet), (ii) 5/8-inch 90° elbow with orifice plate (for venturi outlet), (iii) universal stand (2 legs), (iv) pump assembly, (v) rechargeable NiMH 9V (280 mAh) battery, (vi) 1-liter beakers, (vii) tray, and (viii) 9V battery charger (5-position).

data which were collected by graduate students performing experiments in a laboratory environment and in-class student data which were collected by undergraduate students during an implementation in a third-year chemical engineering fluid flow and heat transfer course (details are provided in next section). During data collection, the flow rate was varied by adjusting the quarter-turn ball valve attached to the supply pumps to be between 3 and 18 mL/s to avoid any air suction in the venturi or water spillage from the top of the manometer, respectively. The measured flow rate, $\dot{V}_m$ was obtained by a positive displacement technique, i.e., dividing the amount of water collected in the exit beaker by the time of flow. The calculated (theoretical) flow rate, $\dot{V}_c$, is determined by applying associated theories as [22].

$$\dot{V}_c = \frac{(\pi d_{th}^2/4)\cdot C_v}{\sqrt{1-\beta^4}}\sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

where $\beta = \frac{d_{th}}{D}$ is the diameter ratio, D is the diameter of the upstream pipe and d_{th} is the venturi throat diameter, ΔP is the pressure drop between inlet and the throat, ρ is the density of fluid and C_v is the venturi discharge coefficient, which accounts for real fluid effects such as compressibility and viscosity as well as loss due to sharp edges [22]. The discharge coefficient for our system has been estimated as the inverse of the slope of a best-fit straight line for Y vs $\dot{V}_m$ curve that passes through the origin, where Y is given as

$$Y = \frac{(\pi d_{th}^2/4)}{\sqrt{1-\beta^4}}\sqrt{\frac{2\ \Delta P}{\rho}} \tag{2}$$

The pressure drop between inlet and throat can be given as

$$\Delta P = \rho g(h_{in} - h_{th}) \tag{3}$$

where h_{in} and h_{th} are the height of the water column in the manometers at the inlet and throat, respectively. To measure the height of the water column in the manometers, we have attached a ruler (graduated in mm) parallel to the manometers. Moreover, to avoid parallax error in the water column height, the measurements were done by taking a high-resolution photograph and analyzing them with data extracting software 'WebPlotDigitizer' [23]. Since water creates a concave meniscus in the manometer, data were read at the lowest level of the concave curve. After passing through the Venturi's throat, the fluid enters the gradually widening diffuser area, which allows for pressure recovery.

The pressure recovery (PR) percentage is calculated by the following equation

$$PR(\%) = \frac{\Delta P'}{\Delta P} \times 100 \qquad (4)$$

where $\Delta P'$ is the pressure gain between throat and venturi outlet which can be given as

$$\Delta P' = \rho g(h_{out} - h_{th}) \qquad (5)$$

where h_{out} is the height of the water column at the outlet standpipe of the venturi cartridge.

2.3 Classroom Implementation Procedure

2.3.1 In-person Implementation

During the in-person implementation, students worked in teams of 2–4 people to complete the experiment with a guided worksheet. For the experimental section, students were first asked to assemble all the components to complete the setup and fill the inlet beaker with dyed water. Dyed water was used to increase the visibility of the water column in the manometers. Once the setup was completed, students were asked to start the flow by starting the pump. After removing any existing bubbles from the venturi, students were required to measure the water height in manometers and collect the water from the venturi exit in an empty beaker. After a specified amount of time, usually ~20 sec, students were asked to stop the flow and measure the water volume in the outlet beaker. Students repeated the experiments for three different valve positions, one fully open and two partially closed, to observe the pressure profiles at different flow rates. After data collection, students completed the in-class part of the guided worksheet which includes (i) self-discussion on velocity and pressure trends and (ii) an exercise using mass and energy balance principles. Students also completed an assessment focused on self-reported engagement and the usefulness of various physical features of the DLM in learning fluid flow concepts.

2.3.2 Virtual Implementation

During the COVID-19 pandemic, we moved completely to a virtual platform for the implementation of DLMs [18, 24]. During the virtual implementation, students were first asked to watch a demo video of the DLM implementation available on our project website. In the video, instructors explain the setup and data collection for three different valve settings: fully open, partially closed 1, and partially closed 2 as is done for in-person implementations. In this demo video, as during in-person implementations, dyed water is used to increase the visibility of the water column in the manometers. In addition, students also watched several other tutorial videos addressing the velocity and pressure trends, energy transitions, and the nonlinearity of pressure and velocity with changing diameter. Moreover, similar to in-class implementations, students completed the in-class part of the guided worksheet with the data shown in the demo video. Students also completed an assessment focused on self-reported engagement and the usefulness of various physical features of the DLM for learning fluid flow concepts.

2.4 Assessment

We hypothesized that in-class/virtual implementation of the venturi meter and completion of the in-class part of the worksheet would increase student conceptual understanding. Therefore, short multiple-choice questions were administered via the Qualtrics XM platform before and after the DLM activity to measure changes in conceptual understanding. The pretest, completed before the DLM activity, had four questions, and the posttest, completed after the DLM activity, had the same four questions and two additional questions. It is noted that question 4 has three parts and, in the results section, these are treated as three independent questions to show the statistics for each part clearly. Since the same pretest questions were introduced in the posttest, there is a chance that the improvement in understanding in the posttest is just an effect of prior exposure to the questions in the pretest. Therefore, additional questions were added to minimize this testing effect [25]. Moreover, the instructor of the course was requested to introduce the pretest and posttest on the same day just before and after the DLM activity, respectively to minimize the effect of double exposition of the questions. However, that was not always possible because of logistics. For in-person implementations in spring 2020, a pretest was taken 3 days before the implementation and for virtual implementations in spring 2021, a pretest was taken 5 days before the implementation. In both cases, however, the posttest was taken on the same day inside or outside of class. We used a digital consent form (in compliance with an IRB exempt determination) to collect student consent to participate in this study and only report data of those students who consented. Table 1 lists the conceptual foci for all pre- and posttest questions. For information on the development of those questions, we refer the reader to prior work by our group [26]. The significance of changes in conceptual understanding before and after the DLM activity was determined by carrying out paired sample Student's t-tests and calculating the Cohen's d effect sizes. But the comparison between in-person and virtual

Table 1. Pre- and post-activity assessments

Question	Conceptual Focus
1	Understanding the energy transformation in a suddenly expanding duct
2	Comprehending pressure profile from a given velocity profile
3	Identification of the most realistic graph for pressure versus distance in the venturi
4 (A/B/C)	Understanding the concept of continuity at steady state for an incompressible fluid. A: Mass flow rate in equals mass flow rate out; B: Volumetric flow rate in equals volumetric flow rate out; C: As diameter decreases, velocity increases
5	Understanding the relationship between changes in pressure and pipe diameter for incompressible fluid flow
6	Identification of the most realistic graph for velocity versus distance in the venturi

implementations was done by using Student's t-tests assuming unequal variances since the same students are not participating in both implementations. Similarly, the significance of score differences between male and female students, both before and after the DLM activity, was also evaluated by using the student's t-test assuming unequal variances. Generally, in statistics, two items are significantly different if the p-value, obtained from the t-test, is less than or equal to 0.05. However, in this study, we considered that the differences between pre- and posttest mean scores are significant if the p-value is less than or equal to 0.1 because with this p-value, the mean scores are differed by 2 to 3 letter grades. In addition to t-tests and effect sizes, the usefulness of DLM for student conceptual understanding and classroom engagement was assessed by introducing a motivational survey after the posttest activity. The motivational survey is primarily focused on the ease of use, useful features of DLMs, and facilitation of learning. Fig. 3 shows the block diagram that illustrates the overall research process.

3. Results

3.1 RQ1: Does the performance of the new venturi meter module mimic the industrial scale counterpart with respect to venturi coefficient and pressure recovery?

The comparison of measured versus theoretical flow rates (Eq. 1), calculated with the most acknowledged literature value of venturi coefficient, $C_v = 0.98$ [27], are shown in Fig. 4. As shown in this figure, both data collected by students in classroom and that carefully collected by PhD candidates show the expected linear relationship between measured and calculated flow rates with slopes 0.95 for the classroom data and 1.04 for the carefully collected data. In both cases, however, calculated flow rates are higher than the measured flow rates. On average, calculated flow rates are 10.2% and 5.7% higher than the measured flow rates for classroom data and carefully collected data, respectively. This indicates that the value of the venturi discharge coefficient, $C_v = 0.98$, used in analysis is not valid for our system. Therefore, to estimate the venturi coefficient for our system, we plotted Y vs $\dot{V}_m$ (see Eq. 2), fitted the data with a straight line that passes through the origin (see Fig. 5), and calculated the venturi coefficient, $C_v = \frac{1}{m}$, where m is the slope of best fit straight line as shown in Fig. 5. The venturi coefficient of our designed system has been estimated to be 0.935 and 0.917 for research group data and in-class student data, respectively. These values of discharge coefficients are close to the reported C_v for laminar flow [22]. With the computed venturi discharge coefficient, there is an excellent agreement between measured and calculated flow rate with errors of a mere 0.1–3.27% as indicated in Table 2. Therefore, the performance of the new venturi meter module mimics the industrial scale counterpart with respect to discharge coefficient.

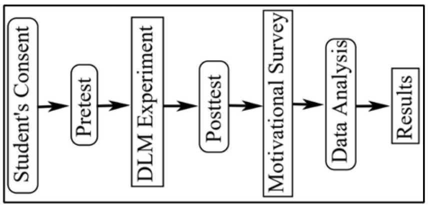

Fig. 3. Block diagram of the research process and student's data collection procedure.

One important characteristics of the flow through the venturi meter is the pressure recovery

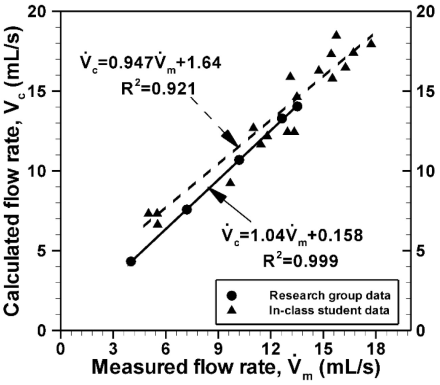

Fig. 4. Theoretical flow rate vs measured flow rate vs, where the former was obtained with a commonly used venturi coefficient, $C_v = 0.98$.

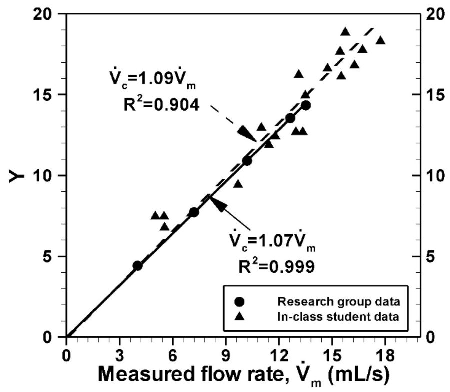

Fig. 5. Estimation of venturi coefficient for our system with research group data (circle) and in-class student data (triangle).

Table 2. Comparison of measured and calculated flow rates (based on research group data only)

Measured flow rate (mL/s) ± SD	Calculated flow rate (mL/s) ± SD	Error percentage (%)
4.00 ± 0.06	4.13 ± 0.02	3.27
7.19 ± 0.04	7.23 ± 0.05	0.63
10.18 ± 0.07	10.19 ± 0.03	0.10
12.62 ± 0.65	12.66 ± 0.13	0.33
13.50 ± 0.11	13.39 ± 0.04	0.82

after passing the throat region. As shown in Fig. 6, the percentage of pressure recovery for our system is low, on the order of 42% and 30% for research group and student data, respectively at Re of 400 ~ 500 (flow rates of 4 ~ 5 mL/s). But the pressure recovery percentage increases to about 60% as Re increases to 1,200 to 1,800 (flow rates of 12 to 18 mL/s). Both research group data and in-class student data show an exponential increase in pressure recovery percentage with increasing Reynolds number. The pressure recovery percentage as well as this exponential growth of pressure recovery with Reynolds number for our system agree well with the literature [28, 29]. Therefore, the performance of the new venturi meter module also mimics the industrial scale counterpart with respect to permanent pressure loss.

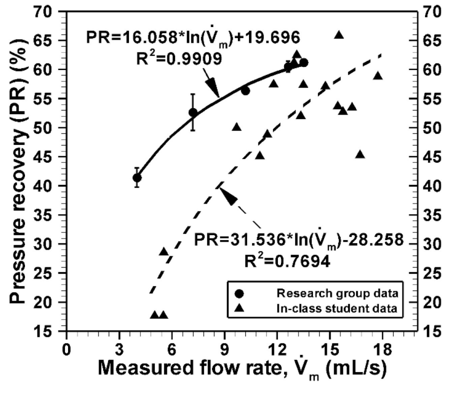

Fig. 6. Percentage of pressure recovery with measured flow rate for research group data (circle) and in-class student data (triangle).

3.2 RQ2: Does the module and associated classroom activity improve student's conceptual understanding significantly, i.e., are there significant differences between pre- and posttest scores?

To check the efficacy, we have implemented our newly designed venturi meter DLM in several undergraduate classrooms. Results from two such representative case studies are presented in Fig. 7. Fig. 7a shows the results in terms of conceptual assessment scores for the multiple-choice tests administered before (pretest) and after (posttest) the activity for an in-person (spring 2020) implementation, while Fig. 7b shows the same thing for a virtual (spring 2021) implementation.

In case of in-person (spring 2020) implementation, as shown in Fig. 7a, there are significant increases in mean scores at the 90% (p = 0.067) and 99% (p < 0.001) confidence levels with small (d = 0.33) and large (d = 0.94) effect sizes, respectively for questions about how the pressure profile relates to the velocity profile (Q2) and identification of the most realistic graph for pressure versus distance in the venturi (Q3). There are no statistically significant differences nor meaningful effect sizes for questions about understanding the energy transformation in a suddenly expanding duct (Q1) and understanding the concept of continuity at

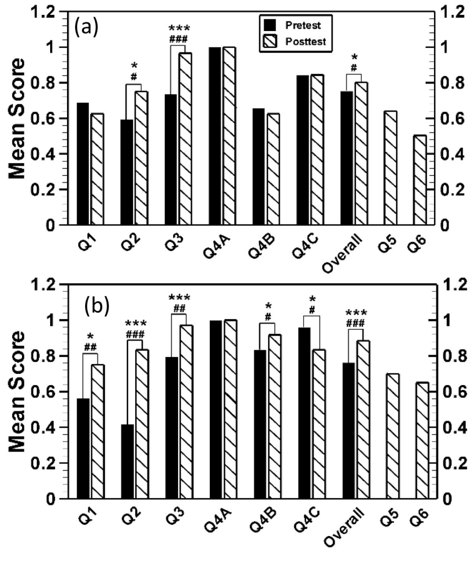

Fig. 7. Student performance for questions asked on both the pre- and posttest: (a) In-person (spring 2020; N = 32) and (b) Virtual (spring 2021: N = 24). In each pair of columns, the first plain filled column represents pre-test scores, and the second hatched column represents posttest scores. *, ** *and* *** *indicate significance at the 90%, 95% and 99% confidence levels, respectively.* #, ## *and* ### *indicate small (0.2 ≤ d < 0.5), medium (0.5 ≤ d < 0.8) and large (d ≥ 0.8) effect sizes, respectively.*

steady state for an incompressible fluid (Q4). However, there still is an overall score increase at a 90% confidence level ($p = 0.091$) with a small effect size ($d = 0.26$) with a respectable average increase from 75% to 80% or what would translate to a grade of C+/B- to a B average.

In case of virtual (spring 2021) implementation, as shown in Fig. 7b, there are also significant improvements in learning on concepts pertaining to understanding the energy transformation in a suddenly expanding duct (Q1), how the pressure profile relates to the velocity profile (Q2), identification of the most realistic graph for pressure versus distance in the venturi (Q3), constant volumetric flow rate at every section of venturi (Q4B) with p-values of 0.065, 0.001, 0.003, 0.081 and Cohen's d effect sizes of 0.41, 0.93, 0.77, 0.25, respectively. However, there is a decrease in score for one question (Q4C: velocity changes as diameter changes) and no change in score for another question (Q4A: discussing mass conservation) among six repeated questions (Fig. 7b). Although the decrease in the score for Q4C is significant with p-value 0.081 and effect size of 0.41, there's a significant overall increase in student scores for the six repeated questions with a p-value < 0.01 and a large effect size of 0.83 with an increase in test average from 76% to 89% translating to a change from a B- to A- level of understanding, something which is desirable by faculty and students. *Therefore, these results indicate that the module and associated classroom activities improve student conceptual understanding significantly.*

Since both representative implementations were carried out in the same course at the same university, this provides us the opportunity to compare between in-person and virtual implementations. Fig. 8 shows the comparative results between in-person and virtual implementations. As seen in Fig. 8a, students participating in the in-person implementation had a better initial knowledge of topics pertaining about understanding the energy transformation in a suddenly expanding duct (Q1) and how the pressure profile relates to the velocity profile (Q2) with effect sizes of 0.27 and 0.35, respectively. The difference between in-person groups and virtual groups was statistically significant (p-value = 0.099) for Q2. Students participating in the virtual implementation had a better initial understanding of subjects covered in Q4B (constant volumetric flow rate at every section of venturi) and Q4C (velocity changes as diameter changes) with significance at the 90% confidence level and 0.41 and 0.38 effect sizes, respectively. By the time of the posttest, the students in virtual implementation surpassed the students in in-person implementation for Q1 and Q2 (Fig. 8b) indicating greater efficacy of virtual implementation. For Q4C, the gap in scores of these two groups is reduced because there is no change in score from pretest to posttest in the case of the in-person implementation, while there is a drop in score from pretest to posttest for the virtual implementation. For Q4B, the gap in scores between in-person and virtual groups is further increased after the posttest as students in virtual implementation outperformed the students in in-person implementation in the posttest resulting in a reduction of the p-value from 0.07 to 0.004. Overall, after the DLM activity, the virtual implementation shows a significantly (p-value = 0.012) higher score than the in-person implementation. This indicates that the virtual implementation is more beneficial for the students.

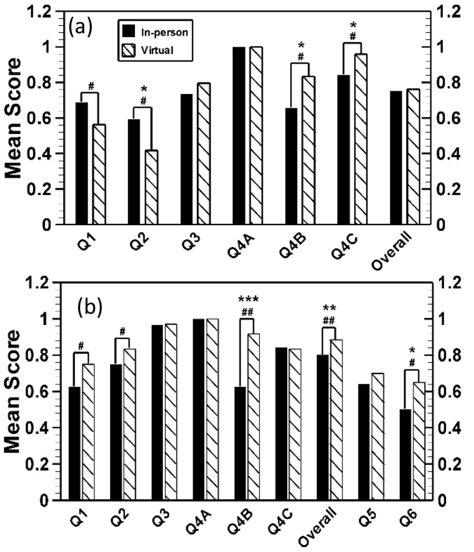

Fig. 8. Question-wise comparison of student performance for in-person ($N = 32$) and virtual ($N = 24$) implementations: (a) Pretest and (b) Posttest. In each pair of columns, the first plain filled column represents in-person implementation scores, and the second hatched column represents virtual implementation scores. *, ** *and* *** *indicate significance at the 90%, 95% and 99% confidence levels, respectively.* #, ## *and* ### *indicate small* ($0.2 \leq d < 0.5$)*, medium* ($0.5 \leq d < 0.8$) *and large* ($d \geq 0.8$) *effect sizes, respectively.*

3.3 RQ3: Does the venturi DLM can reduce the gender gap in the engineering classroom, i.e., to what extent the performance of female students differs from the male students before and after the DLM activity?

The comparative performance of male and female students before and after the use of venturi DLM in the case of virtual implementations (spring 2021) is shown in Fig. 9. Fig. 9(a) shows the comparison of pretest scores, while Fig. 9(b) shows the comparison of posttest scores for male and female students. As shown in Fig. 9(a), except for two questions (Q2 and Q4B) there were no significant differences

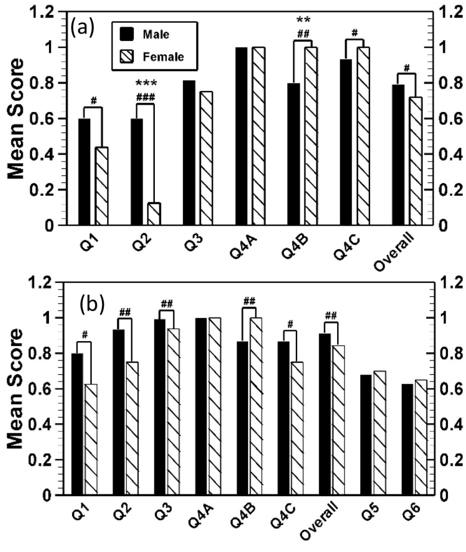

Fig. 9. Comparison of male (N = 15) and female (N = 8) student scores before (pretest) (a) and after (posttest) (b) the DLM and associated activities. In each pair of columns, the first plain filled column represents male, and the second hatched column represents female student scores. *, ** _and *** indicate significance at the 90%, 95% and 99% confidence levels, respectively. #, ## and ### indicate small ($0.2 \le d < 0.5$), medium ($0.5 \le d < 0.8$) and large ($d \ge 0.8$) effect sizes, respectively._

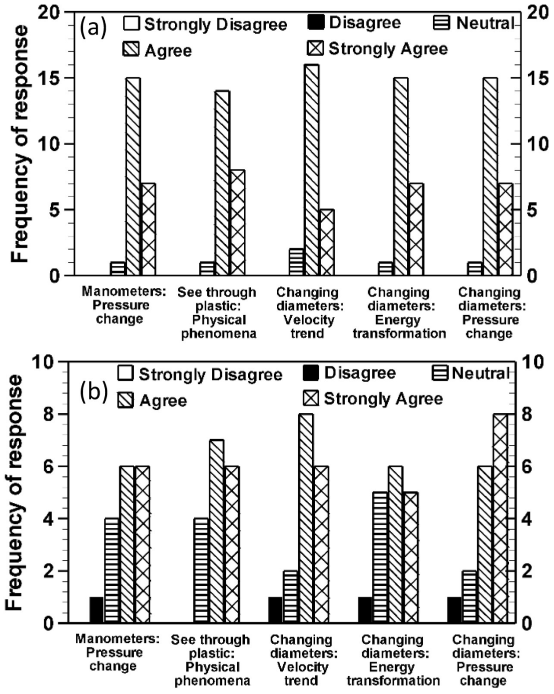

Fig. 10. Likert scale responses on whether physical features of the DLM were helpful for the understanding of the indicated concepts: (a) In-person (Spring 2020) implementation and (b) Virtual (Spring 2021) implementation.

between male and female student pretest scores. In Q2, the average male students score of 60% is significantly (p-value < 0.01) higher than that of the average female (12.5%); while in Q4B, male students score (80%) is significantly (p-value = 0.04) lower than that of female students score (100%). However, as shown in Fig. 9(b), after the DLM and associated activity, female students had a larger average score improvement, 62.5%, from the pre- to the posttest compared to the 30.3% average improvement of male students' scores for Q2. As a result, the gender gap between male and female students for this question is reduced as the gap is no longer significant (p-value = 0.17) after the DLM activity. The gap is also reduced for Q4B from 20% to 13% after the DLM activity resulting in an increase in p-value from 0.04 to 0.1. For all other questions, both male and female students showed near equal improvements after the DLM activity. *Therefore, the venturi DLM reduces the gender gap that exists in the traditional engineering classroom.*

3.4 RQ4: Do students believe that use of the DLM is helpful for achieving gains in their own conceptual understanding and classroom engagement?

To understand the student feelings towards the use of DLM in undergraduate classroom, we have introduced a motivational survey with two sets of questions as post-experimental activity. The results in terms of Likert scale responses for the first set of questions are shown in Fig. 10. Fig. 10a shows the response for the case of in-person (Spring 2020) Implementations while Fig. 10b shows the response in the case of virtual (Spring 2021) implementations. The majority i.e., 91.3–95.7% students for in-person implementation and 64.7–82.4% students for virtual implementation believe that the see-through aspects of the manometers, and plastic venturi meter with changing diameters helped to understand physical phenomena such as pressure changes, energy transformation, and velocity trends.

Responses from the second set of questions related to the potential for increasing engagement are listed in Table 3. As shown, most students, in the 64.5–82.4% range, believe that the DLM activity offers better engagement with the learning process in comparison to typical lectures. In addition, students felt that both in-person and virtual implementation of DLM assist them in deepening their understanding of venturi concepts through visualization. For the in-person group, this extended to discussions of concepts with a peer, while that aspect could not be measured for the virtual group. Moreover, results for the last three questions related to relative engagement show about 48% of in-person and 59% of virtual learning students believe, compared to lecture, they were able to engage with concepts in the same way with DLM associated activities. At the same time 48% (in-

Table 3. Engagement with the DLM compared to lecture

Response	**Disagree (%)**		**Neutral (%)**		**Agree (%)**	
Compared to lecture, the DLM. . .	**In-person (Spring 2020)**	**Virtual (Spring 2021)**	**In-person (Spring 2020)**	**Spring 2021**	**In-person (Spring 2020)**	**Virtual (Spring 2021)**
Helped me to discuss concepts with a peer better	0	–	26.1	–	73.9	–
Helped me to have a deeper understanding of venturi concepts	4.3	11.8	17.4	23.5	78.3	64.5
Helped me to see venturi concepts better	4.3	0.0	17.4	17.6	78.3	82.4
Did not allow me to engage with concepts the same way	47.8	58.8	21.7	17.6	30.4	23.5
Only allowed me to be disengaged	47.8	52.9	17.4	35.3	34.8	11.8
Made me idle	52.2	58.8	30.4	29.4	17.4	11.8

person) and 53% (virtual) students think that the activities allow them to become engaged and 52% (in-person) and 59% (virtual) think that the DLM makes them become industrious. Therefore, most students believe that use of the DLM is helpful for achieving gains in their own conceptual understanding and classroom engagement.

4. Discussions

4.1 RQ1: Does the performance of the new venturi meter module mimic the industrial scale counterpart with respect to venturi coefficient and pressure recovery?

We have estimated the venturi discharge coefficient of our system as a primary parameter to evaluate the performance of the newly built venturi meter. As stated in the results, the resulting flow rates through our system is a laminar flow i.e., $Re < 2300$. According to literature, the venturi discharge coefficients for laminar flow can be given as [22]

$$C_{v,\,laminar} = 0.995\frac{\sqrt{(1-\beta^4)}}{\sqrt{(1-\beta^4)+2.8f}} \tag{6}$$

where $f = \frac{64}{Re}$ is the friction factor, $Re = \rho vD/\mu$ is the Reynold number, v is the average velocity, and μ is the fluid viscosity. Thus, with our data, we should have got a C_v values of 0.82 and 0.95 for Reynolds numbers (Re) of 405 and 1770, respectively. The venturi coefficient of our designed system has been estimated to be 0.935 and 0.917 for research group data and in-class student data, respectively. Therefore, the estimated venturi coefficient of our designed system for both research group data and in-class student data fall within the expected range. Our estimated values are closer to the upper end of the expected range because, during the experiment, most of the data were taken at a higher Reynolds number near the largest possible flow rate for our system (Figs. 4 and 5). In addition, for the same Reynolds number, the venturi discharge coefficient varies with the design of the meter, the viscosity of the fluid, rate of flow, and the surface roughness [18, 22]. Both research group data and in-class student data yield very similar results in terms of discharge coefficients, which indicates that our designed system is very consistent in performance under diverse circumstances. Fig. 5 shows that in-class student data are more scattered than research group data from their corresponding straight line fit. Since in-class student data were obtained by undergraduate students who are using the DLM for the first time with a time limit of 50 minutes, these data are subjected to more error than the research group data. Therefore, the venturi coefficient obtained with research group data is used in further analysis of our system. With the computed venturi discharge coefficient, the calculated (theoretical) flow rate agrees well with the measured flow rate with a maximum error of ~ 3% as indicated in Table 2. This result further supports the comparability of our device with its *industrial scale counterpart.*

In general, the permanent pressure loss of a venturi meter is quite low compared to other differential-pressure devices [28] because with a longer diverging section, most of the kinetic energy is converted back to pressure energy. Therefore, we should expect a higher-pressure recovery for our system. However, as indicated in results (Fig. 6), the percentage of pressure recovery of our system is low i.e., our system yields a high permanent pressure loss. This low percentage of pressure recovery in our system occurs because of very low flow rates, i.e., laminar flow with higher viscous effects. A previous study showed that as the Re decreases the permanent pressure loss in the diffuser increases exponentially [28]. According to the work of Kline et al. [29], for laminar and transition flow ($Re < 4{,}000$), the permanent pressure loss is greater than 50%. Both research group and in-class student data agree with existing literatures showing a logarithmic distribution of pressure recovery percentage with increasing Reynolds number. The maximum pressure recovery for our system is ~ 60% which occurs at $Re \sim 1800$. For a Reynolds number smaller than 1,200, the in-class student data shows a much smaller pressure recovery than research group data because, at low flow rates, bubbles easily can get trapped inside the venturi meter, and as first-time users of DLM, students may not be conscious about removing the bubbles before taking the measurements. But at a higher Reynolds number, this problem is eliminated, resulting in mostly the same percentage of pressure recovery for both research group and in-class student data. Although student data are more scattered, considering the small size and low manufacturing cost, the venturi meter DLM results agree remarkably well with the existing literature, showing its usefulness as a hands-on learning tool in undergraduate classroom settings.

4.2 RQ2: Does the module and associated classroom activity improve student's conceptual understanding significantly, i.e., are there significant differences between pre- and posttest scores?

We hypothesized that our venturi meter will not only allow students to collect accurate quantitative data but also promote meaningful conceptual understanding gains. To test this hypothesis, venturi module was employed in a third-year chemical engineering classroom for two different class room formats (in-person and virtual) at the same university. In these implementations, we tested the efficacy of newly developed venturi meter by comparing the students' conceptual understanding level before and after the DLM implementations. To measure the conceptual understanding level, we have introduced pretest and posttest with 4 and 6 questions, respectively, related with venturi meter concepts. As shown in Fig. 7, both implementations show favorable results as the overall posttest score is significantly higher than overall pretest score. However, careful examination of the results shows that improvement in understanding level really occurred for concepts that are clearly visible in the DLMs due to see through nature. For example, both implementation results show a significant improvement in understanding level after the use of venturi DLM for Q3 (Fig. 7) in which students were asked to identify the most realistic graph for pressure versus distance in the venturi meter. The see through nature of DLMs has the capacity to converts a higher Bloom's level questions into a lower Bloom's level question which helps students to understand the energy transition from pressure to kinetic or vice versa occurring in venturi meter [12]. In addition, it has been found that the interactive group achieve a significantly larger learning gains when learning instructions are paired with higher-level Bloom's activities [30]. The current implementations are in line with the previously published results. For examples, both implementation results show a significant improvement in understanding level after the use of venturi DLM for Q2 (Fig. 7) in which students were asked to select correct velocity profile from a given pressure profile. Although this concept is not directly visible during DLM experimentation, the mental image of pressure distribution eases the application of Bernoulli's principle to deduce the velocity distribution.

The comparative results of in-person vs virtual implementations are shown in Fig. 8. These results assess the impact of prior knowledge on the improvements in conceptual understanding presented in Fig. 7. Our results shows that when pretest score is low, there is a high improvement in conceptual understanding. For example, the average pretest score was low for Q2 (Fig. 8a), however, after the implementation, a high average posttest score is observed for this question. Interestingly, the comparison of in-person vs virtual implementations results (Fig. 8) shows that there is a substantially greater increase in performance on conceptual questions for virtual implementation (spring 2021). While the DLM used in both instances is the same, explanation for the difference may reside in the ancillary use of conceptual videos with the virtual implementation where concepts related to velocity profile, energy transitions, and pressure profile are clearly outlined for students. In addition, the virtual group enjoyed the extra time to think and discuss the subject matter since they did not spend the time doing experiments and data collection. Although it can be concluded based on the current evidence that virtual implementations with video demonstration work better than standalone hands-on experiments, further study in this area including hands-on experiments with more guided instructions or video demonstration is needed to make a more concrete conclusion.

4.3 RQ3: Does the venturi DLM can reduce the gender gap in the engineering classroom, i.e., to what extent does performance of female students differ from the performance of male students before and after the DLM activity?

Students have individual learning preferences including visual–learning from graphs, charts, and flow diagrams, auditory–learning from speech, read-write–learning from reading and writing, and kinesthetic–learning from physical activity [31]. Especially male and female students have significantly different preference for learning styles [32] which creates a gender gap in the engineering classroom. The teaching and presentation of most engineering courses would be more effective for most students if they contained elements which appealed to all learning styles. Therefore, we have created the DLM to incorporate interactive, sensing, visual and sequential learning components in the engineering classroom. Lorenzo et al. [33] showed that interactive teaching strategies not only yield significantly increased understanding for both males and females but also reduce the gender gap. However, Pollock et al. [34] obtained an opposite result showing that interactive engagement techniques do not necessarily reduce the gender gap. Since our target is to transform learning environments to be more interactive and experiential, therefore, it is very relevant to compare the performance of male and female students before and after the use of venturi DLM. To determine whether our venturi DLM activity was equally beneficial for female and male students, the pre- and posttest scores for the conceptual assessment questions in the case of virtual implementations (Spring 2021) are compared in Fig. 9. These results were created by separating the data presented in Fig. 7b for male (N = 15) and female (N = 8) students. As shown in Fig. 9a, for two questions (Q2 and Q4B) there were significant differences between male and female student pretest scores. However, after the use of venturi DLM, there were no significant difference between female and male student scores as shown in Fig. 9b. Therefore, this representative data suggests that DLMs are equally useful for both male and female students and they help to reduce the gender differences: in one case improving performance of female students and in the other case improving the performance of male students. Thus, our DLM offers active, sensing, visual, and sequential learning as these learning strategies are preferred by both male and female students [35]. However, further study in this area, as well as use of DLM for improving the performance of low-achieving and disadvantaged/minority students as conducted for other interactive activity studies [36, 37], is highly recommended.

4.4 RQ4: Do students believe that use of the DLM is helpful for achieving gains in their own conceptual understanding and classroom engagement?

As a post-experimental activity, a motivational assessment tool was used to determine the perceived usefulness and engagement when using DLMs in-person or virtually. The motivational survey consists of two sets of questions. The first set of questions were asked to examine student feelings about different striking features of the DLM in relation to how those features helped to improve student conceptual understanding, while the second set of questions were asked to examine the student engagement during the DLM activity.

As stated in the results, for both (in person and virtual) implementations, most students agreed that the physical features of DLM help them to understand physical phenomena such as pressure changes, energy transformation, and velocity trends. For the virtual instruction, however, there were a larger percentage of students (ranging from 11.8 to 29.4%) who were neutral in their responses. One student (0.06%) even disagreed with the fact that the activities helped with understanding (Fig. 10b). This at least shows some feeling of a disconnect with understanding when students do not get to touch the equipment physically, though posttest scores show a marked improvement for these students over the hands-on group. Again, the gain in posttest score may be because much of the information content was supplemented through video instructions. Overall, these results are in line with other studies, which show hands-on activity in STEM courses reinforce student confidence in their conceptual understanding [38, 39].

As listed in the Table 3, most students ($\sim$ 75%) believe that compared to lecture, the DLM helped them to discuss the concepts with their peer, have a deeper understanding of various concepts, and visualize the venturi concepts better. In addition, more than 50% of students agree that DLM allowed them to engage with concepts the same way or better than lecture and made them active. Therefore, these data tell that the DLM offers students the opportunity to engage with the learning process in an interactive way. This interactive learning opportunity helps them to better understand the subject matters as displayed by the overall higher posttest score than the overall pretest score (Fig. 7). These results are in line with the ICAP hypothesis [40], which predicts that as students become more engaged with the learning materials, from passive to active to constructive to interactive, their learning will increase. Student engagement is a recognized key indicator of student learning interests. Therefore, taken together, the results from the engagement and perceived usefulness questions indicate that the activities associated with the DLMs whether in-person or virtual are both valuable for conceptual understanding and classroom engagement.

5. Conclusions

In this paper, we have addressed the design, fabrication, and classroom implementation of a next-generation desktop-sized venturi meter which was fabricated from two mirror-image halves of injection molded polycarbonate plastic which ensures transparency, excellent reproducibility and low cost. The robot-assisted joining of two halves with UV-curable adhesive ensures dimensional consistency as well as structural integrity. Quantitative measurements reveal that the venturi meter DLM developed is useful for the accurate measurement of flow rates and pressure recovery with a high coefficient of discharge. Although the pressure recovery percentage is small compared to industrial counterparts, the results are in line with available literature dealing with low Reynolds number flow. Implementation in the undergraduate classroom reveals that both the associated hands-on experiment and virtual counterpart are useful in addressing student misconceptions about velocity and pressure profiles, and flow continuity in a venturi meter. There is a definitive increase in overall understanding when using the demonstration/virtual mode of instruction and we attribute this to the companion conceptual videos that accompany the virtual implementation. In both cases student surveys underpin the importance of highly visual physical features used in the implementations are important in transmitting conceptual understanding. The small-scale prototype makes the DLM highly flexible for a variety of classroom applications. Therefore, it can be concluded that the venturi meter DLM as developed can be used to provide effective hands-on or virtual learning experiences to undergraduate chemical and mechanical engineering students.

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