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Capabilities of Desktop Scale Heat Transfer and Fluid Mechanics Equipment for Classroom Instruction*

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Miniaturized fluid mechanics and heat transfer systems have been developed for classroom learning of flow measurement, hydraulic loss, and heat exchanger concepts. This equipment produces measurable, predictable temperature and pressure changes using tap water across a narrow flow range. Herein the capabilities of the equipment, agreement with correlations, and evidence of suitability for classrooms are provided. Analysis of student comments, from open-ended survey questions given to a total of 52 students over two semesters, is generally positive with students finding added value from using the equipment.

Keywords: hands-on learning; miniature heat exchangers; industrial correlations; miniature fluid flow equipment

1. Introduction

During the course of refining a novel cooperative, hands-on, active, problem-based pedagogy in a fluid mechanics and heat transfer course [1], the authors realized that, in order to facilitate adoption by others, they needed to develop equipment that would allow students to easily perform brief experiments using common industrial equipment in a standard university classroom instead of a laboratory. One of the key features of the authors' pedagogy is enabling students to gain a physical understanding of the correlations they are learning to use. For example, students learn to use the Donahue equation to predict heat transfer on the shell side of a shell and tube heat exchanger. Having a working shell and tube heat exchanger with a see-through shell is especially useful in gaining understanding of design parameters such as the size of the baffle window and crossflow tube pattern, which affect the average mass velocity on the shell side.

Though the archives of *Chemical Engineering Education* contain a broad variety of low cost, in-class experiments, none provide students with experience on industrial style equipment. Existing experiments focus instead on low cost, easy to obtain materials that can be used to illustrate a range of points. Some examples include using an ice cream maker to teach process engineering [2]; examining what happens when pop goes flat [3]; simple experiments with a stir-plate and ice bath to examine kinetics, heat transfer and sensor dynamics [4]; using a mug warmer and CPU cooling devices for studying heat transfer [5]; and a personal favorite of one of the author's uses a cup of coffee to teach transport phenomena [6]. While this style of experiment can work quite well, the authors' pedagogy was developed for a course that deals with sizing piping systems and heat exchangers. It is very difficult to find, for example, a shell and tube heat exchanger on this small of scale, and those that are commercially available are expensive and are not constructed out of see-through materials so that students can view and understand the inner workings. Shell and tube heat exchangers, in particular, do not have analogous simple systems that may be used for teaching purposes. To successfully move their pedagogy into a standard classroom, the authors needed to develop very small scale versions of industrial style heat exchangers and flow measurement devices.

The new system needed to be capable of duplicating the range of activities performed with its non-desktop scale predecessors [1] except be essentially self-contained, that is not requiring water or power hook-ups that might not be available in a standard classroom. Further, running extension cords to outlets would result in tripping hazards. The supply water should be from the domestic water system, namely hot and cold tap water, which can be brought to the room in buckets from whatever location is most convenient.

The resulting apparatus, called the Desktop Learning Module (DLM) [7–14], has a footprint of one square foot, to fit easily on a desk or table, and contains all the necessary instrumentation, supply water tanks, and battery power required for operation. These apparatuses, being realistic miniaturized versions of equipment, may also be used in a unit operations laboratory [15]. Wherever possible, the equipment is transparent so that students can see the inner workings. The key idea is that

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this system is meant to be portable, easy to use, adaptable to a wide range of spaces, and safe. Adaptability is provided by placing the systems of interest on interchangeable cartridges. Though other cartridges, such as a weir and flume, are in development in order to extend the utility of the DLM [13, 16], the following are the chemical engineering cartridges with a mature and stable design: a venturi meter, orifice meter, double pipe heat exchanger, shell and tube heat exchanger, extended area heat exchanger, and a packed/fluidized bed.

This article describes the capabilities of the DLM. It begins with a brief description of the DLM, which consists of a base unit with interchangeable cartridges, and then proceeds to some important technical questions to answer about DLM and cartridge performance [7]: (1) Can the system be easily used in either a classroom or laboratory setting? (2) Are the operating ranges broad enough to encompass the full range of flow rates common to industry? (3) Can a given heat exchange cartridge produce measurable temperature changes when cooling hot tap water (~120°F (49°C)) with ambient air (~70°F (21°C)) or cold tap water (~45°F (7°C))? (4) Will the system reach pseudo-steady state operation quickly enough that many student groups can rotate through a DLM station and have a hands-on learning opportunity? This is especially important for programs that might have 100–300 student class sizes (with the larger range common in some international programs), even in upper level courses within a major, and limited numbers of DLMs due to space and budget constraints [7]. A related economic question, will these units be of low cost such that an academic department will be willing and able to buy five or six? is not answered in this article. (5) Are there anomalies in the system that make for good engineering learning experiences? (6) Do these miniature units portray operating characteristics similar to that of full size units? If so they can be modeled with industrial correlations; if not, they can lead to a discussion on the limitations of industrial correlations. This last question is of particular interest. One of the authors recalls many discussions among chemical engineering seniors in the unit operations laboratory, where students dismissed disagreement between correlations and the data they collected from a relatively small, 16 ft^2, industrial shell and tube heat exchanger as being due to the correlations not being valid for heat exchangers that small. The DLM heat exchangers are an order of magnitude smaller. Some of these questions will be taken individually, while others are better answered within the context of discussion of the features of individual interchangeable cartridges. Operating ranges and opportunities for improvement are part of the discussion of each cartridge's features. Following that, student responses to the DLMs, as recorded in their written comments on surveys, have been analyzed and a discussion is included. Finally, there are a few concluding remarks regarding how well the DLM fits its intended purpose and summarizing the future development of the concept. We want to emphasize this article is focused on answering the above technological questions in use of miniaturized hands-on equipment; for publications highlighting associated pedagogical gains, including enhanced scores on concept quizzes and inventories and improvement in classroom performance, and abundant survey information aligning DLMs with the 7 Principles of Good Practice in Undergraduate Education [17] we refer the reader to our numerous other articles on the subject [1, 7, 10, 18–29].

1.1 Theoretical foundations

DLMs are an enabling technology which may be used to support instruction in ways described by multiple learning theories. By design, DLM use supports experiential and constructivist learning theories. Specifically it provides in class opportunities for instructors to guide students through Kolb's learning cycle [30, 31] of abstract conceptualization, active experimentation, concrete experience, and reflective observation. DLMs specifically provide opportunities for students to interact with a working model representing the theories they are learning about and verify whether their hypotheses are correct. It provides a platform in which students can have concrete experiences and perform active experimentation.

DLMs have been used in highly structured cooperative learning environments [10, 23] as a platform around which peer teaching can happen. Used in this manner, DLMs provide a set of systems with a consistent interface. Individual students or groups can be assigned the task of developing a lesson and activity to guide their fellow students through Kolb's learning cycle for one of the systems available as a DLM cartridge. In this way, each student learns the overall course content, while simultaneously gaining some degree of expertise in a specific topic. DLMs can also be used in less structured group learning environments wherein each student group is given an instructor developed learning activity to work through. DLMs provide an effective means to enact longer term group activities in a course.

Recent learning theories indicate that learning activities for non-experts increase effectiveness as they proceed from passive to constructive to active to interactive (the ICAP hypothesis) [32]. DLM activities are inherently active as they force students to physically act to manipulate the equipment to complete a learning activity. It is relatively easy, from this starting point, to develop an interactive activity that would help students discuss as they accomplish the activity, thus providing an environment which should increase learning. DLM activities may be designed using the ICAP framework either for research or educational purposes.

DLMs further provide opportunities to develop correct mental models as they observe and interact with physical phenomena. In addition to providing a concrete example for new phenomena, this can provide opportunities to directly challenge and correct misconceptions. Mental models and schema are an important part of what separates experts from novices in a field [33, 34]. Providing more opportunities to challenge a student's thinking should be an important part of developing expertise. DLM activities can be designed in such a way as to illuminate misconceptions, forcing students to grapple with the resulting cognitive dissonance.

DLMs may also help reduce extraneous cognitive load for students. Cognitive load theory postulates that a learning task imposes three different types of demands on a student's working memory [35]: Intrinsic load—the demands inherent to the problem and how it is presented; extraneous load—the extra mental demands that detract from the student's ability to learn; germane load—the extra mental demands that assist in the student's ability to learn. Functional, physical system models, such as DLMs, should be able help an instructor reduce intrinsic load by not demanding that students imagine a system or interpret a drawing while simultaneously wrestling with course concepts.

One of the recent thrusts of our research group has been to evaluate how active and hands-on learning environments affect student's motivation to learn engineering concepts. DLMs have been a key component of the learning environment for this work [36]. This portion of our work utilizes motivational and self-efficacy theories.

As the preceding paragraphs show, DLMs enable the use of a wide variety of learning theories from either a research or instructional design perspective. They are not dependent on any one learning theory, but rather can support instruction methods that make use of a wide range of constructivist learning theories. As with any such enabling technology, the instructor or researcher is free to design activities in accordance with theory and make use of the DLMs in the way they best fit.

2. DLM description

The DLM base unit shown in Fig. 1 has a 12 in. (30.5 cm) by 12 in. (30.5 cm) by 15 in. (38.1 cm) cubical shape and contains digital readouts, immediately above an interchangeable cartridge to display process temperature and pressure drops, and analog rotameters, in the 5 to 70 gallons per hour (GPH) (5.3–73.6 ml/s) range, to provide process flowrates. Type K thermocouples are built into the base unit, and differential pressure transducers are built into each cartridge. One-gallon hot and cold reservoirs, seen at the top left of the photo, are used to feed centrifugal pumps, located beneath the system, which provide flow to the cartridge. Flow can either be returned to a reservoir or routed to a waste stream. Fig. 1 shows that the unit is designed such that multiple individuals can simultaneously view the process being driven by the learning module. Handles aid in portability and a leveling indicator may be used to aid in adjusting DLM feet for slightly slanted surfaces. The base unit also has an analog output port, currently a nine pin D-sub connector, which may be used to log the temperature and pressure data. Though we currently use a Measurement Computing USB-1608FS data acquisition device and a data logging program, written using SoftWire (Measurement Computing), any appropriate computerized data acquisition system could be used.

2.1 Safety

DLMs are designed for use in classroom rather than laboratory spaces. For this reason, we have taken extra care and attention with regard to safety. To begin with, the DLMs operate using tap water. This

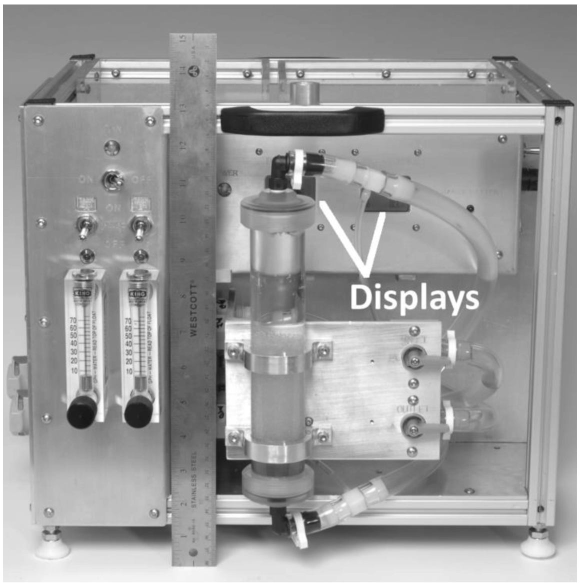

Fig. 1. Base desktop learning module with fluidized bed cartridge inserted. Shown are rotameters, on-off switches, and hot and cold water reservoirs. Digital displays for temperatures and pressure drops are just visible behind the tubing, directly above the cartridge.

eliminates chemical hazard concerns. Another concern in a crowded classroom is tripping hazards. By making DLMs self-contained, we have eliminated tripping hazards associated with extension cords or water hoses. This also serves to minimize concerns coming from having water and electrical apparatus in close proximity. While this is still a concern, the low wattage of the equipment serves to minimize the risk. The remaining slipping hazard is that caused by water spills creating a slippery floor. Avoiding this hazard will require care and attention on the part of both student and instructor, both to prevent and quickly mitigate any spills. With regard to personal protective equipment (PPE), without any chemical or overhead hazards, both laboratory coats and hard hats should be unnecessary. The sole remaining hazard is physical damage to someone's eyes due to splashes or leaks in a pressurized part of the apparatus. Pressures in the apparatus are less than those in household water pipes. In the worst case, if a pressure tap line bursts, there isn't enough pressure to cause the tubing to start waving around. The physical layout of the equipment also means that in this case, any spray would largely impact the apparatus rather than being directed outward toward students. Therefore, there isn't a need for protective eyewear, though it may be advisable from the standpoint of helping students build good laboratory habits. Having a class think about and evaluate the hazards inherent in this equipment would be a very good exercise.

2.2 Ease of use

The modular nature of the DLMs makes them easy to use in that it provides a consistent user interface across a variety of experiments. Pressure and temperature measurements are always on the same screen, and the flow rate is easily adjusted with immediate visual feedback. Start-up and shutdown procedures are also consistent across the cartridge range.

2.3 Alternatives

There are, of course, alternatives that can provide experiential learning opportunities for students. The first, and most traditional, of these is to provide a separate laboratory experience that goes along with the course. While this does provide the desired concrete experiences, and can do so with greater flexibility and in greater depth, it does require larger spaces, more expensive equipment, more time from the students, and more credit hours.

Another option is to have computerized simulations of the equipment. This eliminates the space requirements and could be implemented in a manner that eliminates the need for extra time and/or credit hours, however computer models tend to produce an idealized set of data. If the point of the experiential learning being implemented is to give students a greater connection between theory and reality, then computer models are less likely to support this goal. While computer models avoid the expense of laboratory equipment, there is an expense involved in both software and hardware to support the modeling system.

A third alternative would be to provide the students access to videos or animations showing the equipment in operation or diagramming the fluid flows or heat transfers being examined. While this can be an excellent way to augment a student's understanding and show concepts that may be difficult to imagine, videos or animations do not provide the opportunity for active experimentation that is a central component of experiential learning. Many professors also express difficulty in finding appropriate material that is at the desired depth. These professors also profess a lack of time or money to create appropriate materials themselves. A similar alternative would be to provide students with static nonfunctional models of the equipment that they could examine. This type of experience could assist students in gaining understanding of the physical shape and reality of the system which can be especially helpful with some flow and heat transfer concepts as they relate to baffle spacing and baffle window geometry when dealing with a shell and tube heat exchanger. However, this again does not provide the opportunity for active experimentation.

A final alternative would be the small cheap easy to construct classroom experiences discussed in the introduction. Per that discussion, these experiences do not provide extensive realism. While they can do an excellent job of highlighting and examining phenomena, the phenomena is not situated within a realistic scenario. Providing that linkage becomes an exercise in imagination.

Desktop learning modules provide opportunities for active experimentation and concrete experience situated within a realistic, though miniaturized, apparatus. They do not require specialized spaces. And while more expensive than many of the experiments that instructor can rig together from common items, they are significantly less expensive than most laboratory equipment.

3. DLM capabilities

Herein we document the capabilities of the miniature interchangeable DLM venturi and orifice meter; shell and tube, double pipe, and extended area heat exchange; and packed/fluidized bed cartridges that have been developed, as pictured in Fig. 2. Cartridge discussions are in a common

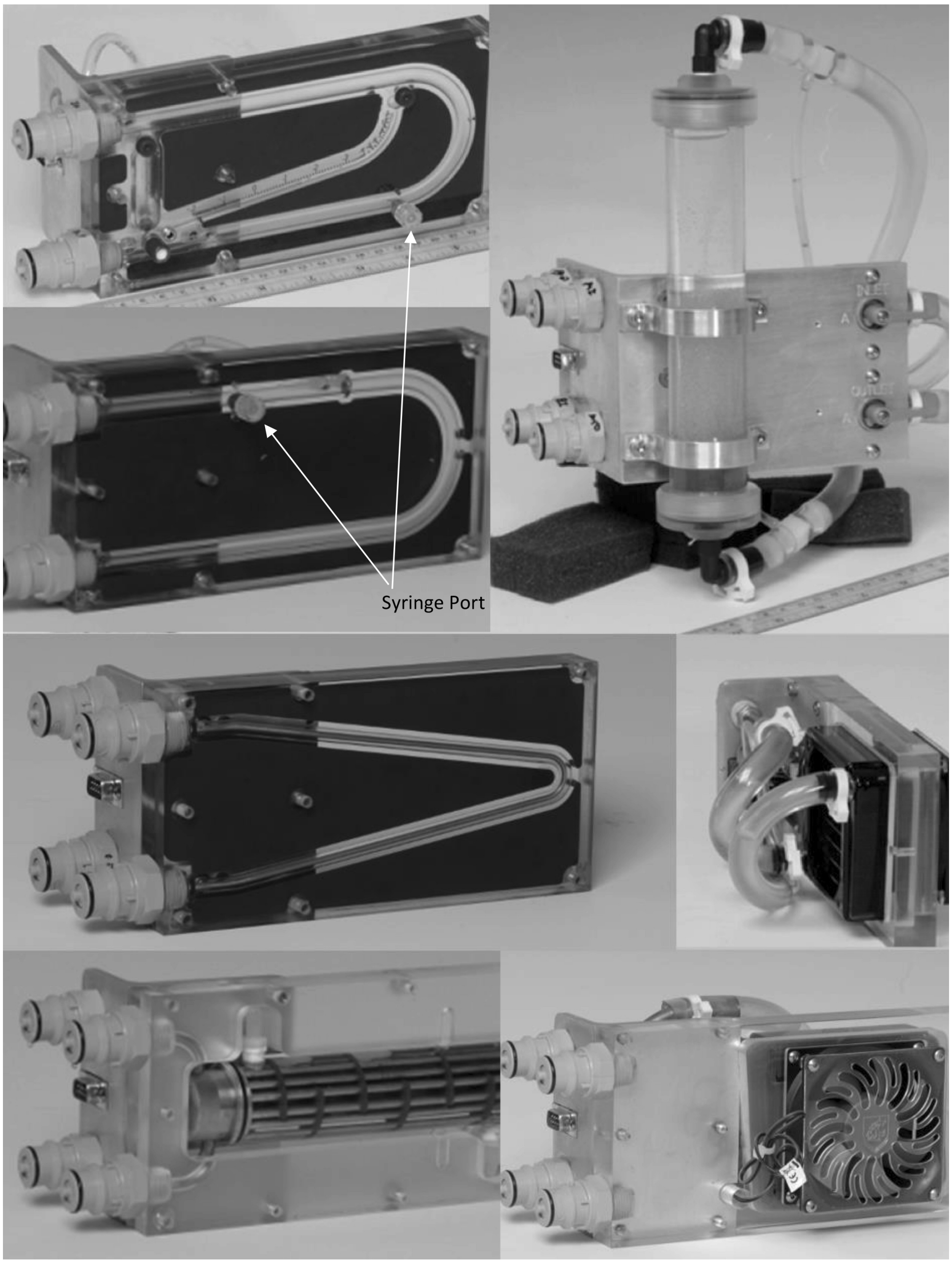

Fig. 2. Clockwise from the top left: Multi-function venturi cartridge, packed / fluidized bed, extended area heat exchanger (rear), extended area heat exchanger (front), shell and tube heat exchanger, double pipe heat exchanger, and orifice meter.

format: A brief written description, detail on the cartridge capabilities and comparison to theoretical values, a discussion of non-idealities and conceptual difficulties that the cartridge will highlight, and prospective improvements to the DLM cartridges. In the interest of saving space, tables, with the physical parameters and operating ranges, and charts, that serve to illustrate the capabilities of the unit, are combined wherever possible. Error bars on these charts are based on the manufacturer's stated error in rotameter readings, 5% of full scale or 3.75 GPH (3.9 ml/s) in the x-direction, and one standard deviation for the data in the y-direction. It should be noted that the rotameter's error ranges from 75% to 5% of the reading for the low to high flow rates, respectively. An average of 10 flow measurements at a rotameter reading of 5 GPH gives 1.44 GPH (1.5 ml/s) with values ranging from 1.1–1.7 GPH (1.2–1.8 ml/s). A preliminary overview of this data may be found in Golter et al.'s 2008 ASEE Global Colloquium paper [8]. The data presented in the present paper is provided in much greater detail and spans a broader range of operating conditions.

3.1 *Multi-functional flow: venturi and orifice meter cartridges*

Both the venturi meter and orifice cartridges in Fig. 2 consist of a U-shaped channel with a circular cross section, machined into clear acrylic, and dye injection port. The venturi meter cartridge also includes an inclined manometer. The straight sections of the U are approximately 6 in. (15.2 cm) long. Table A-1 lists the operating ranges and relevant dimensions for these cartridges with subsequent sections devoted to the various subunits within this cartridge.

3.1.1 *Reynolds experiment*

Upstream of either the venturi or orifice is a dye injection port for conducting the Osborne Reynolds experiment, as shown in Fig. 3. This consists of a Luer-Lok fitting that receives a small syringe used to inject dye into the flow stream. A short section of hypodermic tubing, bent at a 90° angle, extends into the flow tube and is aligned with the center of the channel. With this set-up, students can clearly observe the transition from laminar to turbulent flow and calculate corresponding Reynolds numbers.

3.1.2 *Venturi meter*

The venturi, Fig. 3, has a 0.25 in. (6.35 mm) ID tube with a 0.16 in. (4.06 mm) throat and is connected to a differential pressure transducer through pressure taps located just before the venturi entrance and at the throat.

3.1.3 *Orifice meter*

The orifice meter has a 0.25 in. (6.35 mm) flow channel and a 0.125 in. (3.175 mm) orifice. This meter is again connected to a differential pressure transducer. Fig. 2 shows the orifice cartridge. Operating ranges and dimensions are in Table A-1. A detail picture of the Orifice, Fig. 3, shows that it is a sharp-edged orifice plate, with the sharp edge on the upstream side.

3.1.4 *System pressure drop*

In the venturi cartridge, the design feature having the larger diameter manometer section requires that a size transition be made in the curve. This makes predicting overall pressure drop for the cartridge a challenge to the students in that there is no standard head loss coefficient for this situation. In this case, the contraction is spread out over the entire length of the U-bend, and results in a change of 1/16 in. (1.59 mm) in the diameter. However, the extra pressure drop from this will be negligible compared to the noise in the measurement and provides an excellent learning exercise for the students on relative magnitudes of pressure drop contributions. In the end, the students can model this as a U-bend acting as a long radius 180° fitting, with a radius to diameter ratio of approximately 5:1.

Because of the similarity in cartridge design, the orifice cartridge pressure drop may be calculated in the same manner, however it does not contain the larger diameter section. Fig. 4 includes a comparison of the theoretical versus measured pressure drops for these cartridges.

3.1.5 *Implications for education and improvement*

As with all of the DLM cartridges, these cartridges are clear, allowing the students to see and discuss the equipment, and more importantly where the correlations and the equipment match up. The cartridges themselves are nicely non-ideal. The measured venturi coefficient of 1.09 is similar to that expected for a well-designed venturi, 0.98, though it is also physically impossible to have a venturi coefficient greater than 1.0. This provides an opportunity to discuss errors in measurement and their effects on calculations. Though we have removed this data in the interest of saving space, the observed spread of

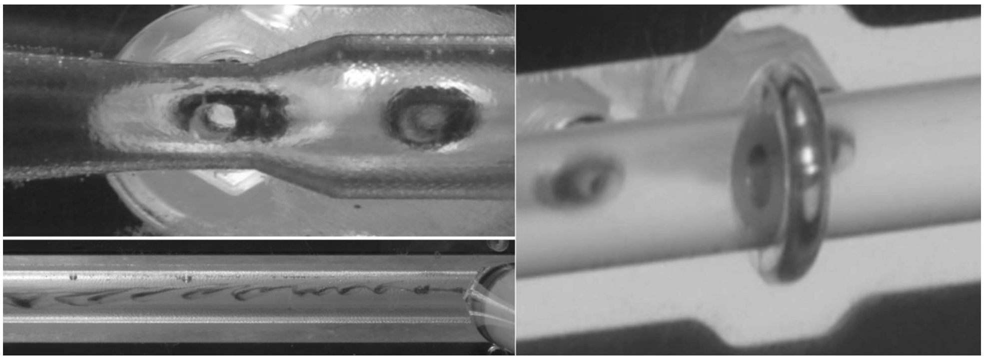

Fig. 3. Top left: Close-up view of the venturi meter. The pressure taps are visible on the backside of the cartridge. Bottom left: Dye injection port in operation with food coloring being injected into the flow stream. Right: Close up view of the orifice plate showing the shape of the orifice opening and the positioning of the downstream pressure tap.

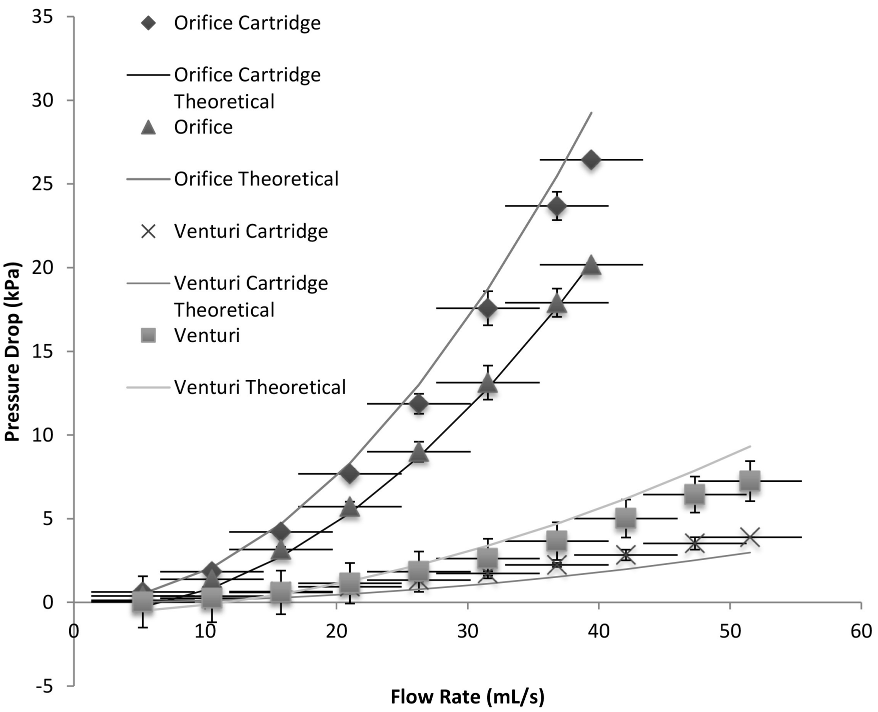

Fig. 4. Comparison of theoretical and average measured pressure drop for the venturi and orifice cartridges.

data and the poor fit of the line ($R^2 = 0.7$) used to calculate the coefficient, using a coefficient of 0.98 is entirely reasonable. The 0.63 orifice coefficient agrees with the 0.61 value reported in standard textbooks.

The upstream pressure tap for both the manometer and the entire cartridge, as well as that in the orifice cartridge, are close enough to the cartridge inlet that a fully developed velocity profile cannot have been developed, the rule of thumb being a minimum of 20 pipe diameters. The current operating range is entirely within the transitional range, which makes finding pressure drop correlations more difficult. This non-ideality provides an opportunity for students to grapple with issues that can affect real, rather than simulated, systems, while still providing an opportunity to observe phenomena in action. On the other hand, there are simple things that can be done to improve the next generation DLM venturi cartridge, notably repositioning the pressure taps. We are also currently evaluating alternative pumps and flowmeters that will increase the operating range of the DLM. There are also difficulties finding a manometer fluid that functions well in this cartridge, as there is a surface tension effect that causes dyed manometer fluids to form droplets in the manometer.

3.2 Shell and tube and double pipe heat exchangers

3.2.1 Double pipe heat exchanger

The double pipe heat exchanger has an overall length of 12 in. (30.5 cm) and consists of two 6 in. (15.2 cm) sections connected at an 18.6° angle with a 0.36 in. (9.14 mm) radius. The inner pipe is standard 1/8 in. (3.18 mm) OD copper tubing and the outer pipe consists of a 0.25 in. (6.35 mm) diameter channel machined into the acrylic. However, differing dimensions and materials may be implemented. Altering the tubing (or channel) diameter, material, or overall length prior to construction would be relatively trivial changes.

3.2.2 Shell and tube heat exchanger

The miniature two tube pass, one shell pass 24 tube shell and tube heat exchanger with 1/8 in. tubes is well described elsewhere [15]; though its capabilities will be discussed for completeness. As can be seen in Fig. 2, the clear acrylic outer shell allows students to see the baffle and tube arrangements rather than having to rely solely on sketches to understand this.

3.2.3 Flow range

Both units operate across a reasonable range of flow rates. Reynolds numbers on the tube side for both systems span from the laminar to the transition range and into the near turbulent range for the annular side of the double pipe system. For the shell side of the shell and tube heat exchanger all Reynolds numbers are above the minimum reported value of 38 used when developing the Donahue equation [37].

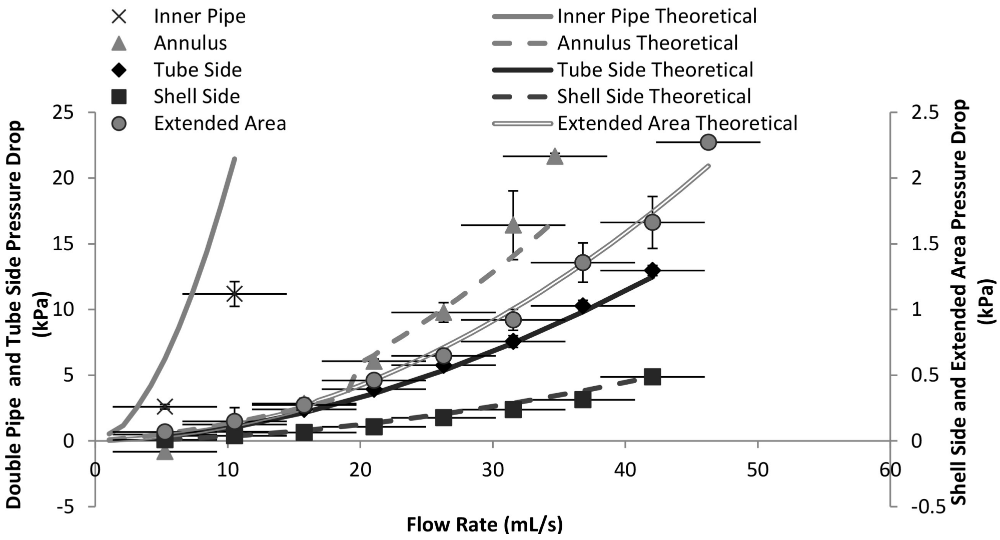

Fig. 5. Pressure drop measurements and calculations for the double pipe heat exchanger, shell and tube heat exchanger, and extended area heat exchanger cartridges.

3.2.4 *System pressure drop*

The pressure drops for both the double pipe and the shell and tube heat exchanger are consistent with theoretical predictions as shown in Fig. 5. For the double pipe and the tube side of the shell and tube, theoretical predictions are made using standard friction loss analysis for smooth pipes, smooth pipes in parallel, and an annulus. The pressure drop for the shells side of the shell and tube is found using the method outlined in the heat transfer equipment design section of Perry's Chemical Engineers Handbook [38]. Both sides of the shell and tube heat exchanger agree within 10 to 100%, and the annular side of the double pipe agreeing within 44 to 100%. The only values that appear out of line are the inner pipe values for the double pipe exchanger where agreements are within 143 to 627%, but this is attributed to poor rotameter accuracy at low flow rates. Given that measured flow rates at a rotameter reading of 5 GPH are low, one can argue that these data points should be shifted accordingly. Since the x-direction error bars on Fig. 5 take this into account, and the x-direction error bars for the inner pipe pressure drop of the double pipe heat exchanger do cross the theoretical curve, the large difference between measurements and theory are explained.

3.2.5 *Heat transfer*

More importantly for instruction on heat transfer, heat exchange data are consistent and show very good agreement between correlation and experiment. This is illustrated in comparison of heat duties over the full range of flow rates reported in Table A-2 where predicted and measured heat duties agree within 27 to 71% for the shell and tube and within 29% for the double pipe heat exchanger at the upper ranges in flow rate where inaccuracies in rotameter readings are a smaller percentage of the overall reading. Fig. 6 shows double pipe temperature profile data and corresponding heat duties for hot and cold streams for a specific experimental run in which the tube (hot-side) was alternated between 5 and 35 GPH (5.3 and 36.8 ml/s) while the annulus (cold-side) flow rate was held constant at 5 GPH (5.3 ml/s). Between each change, the system reaches a pseudo-steady state within 10 seconds and is held there for at least 30 seconds until the next alteration in flow rate. Here we notice that differences between a hot and cold stream heat duty as determined by energy balances are within 0–31%. Another observation is that because the heat exchanger effluent is remixed with the reservoir tanks, we see a steady decline of inlet temperature of the hot stream, and a steady incline of the cold stream. However, all that is needed is a set of temperatures and flow rate data at a given time point for a complete analysis of the system.

3.2.6 *Implications for education and improvement*

Further reflection on DLM shell and tube and double pipe heat exchanger data and experiences in collecting data reveal excellent learning opportunities for students. Regarding frictional losses, the measured pressure drop for the system, Fig. 5, corresponds well with pressure drops that would be calculated from theory. The bump in the predicted annular pressure drop curve, at approximately 17 GPH (17.9 ml/s), is caused by the transition from laminar to turbulent flow between 11000 and 19000 Re. Again, this apparatus is not a

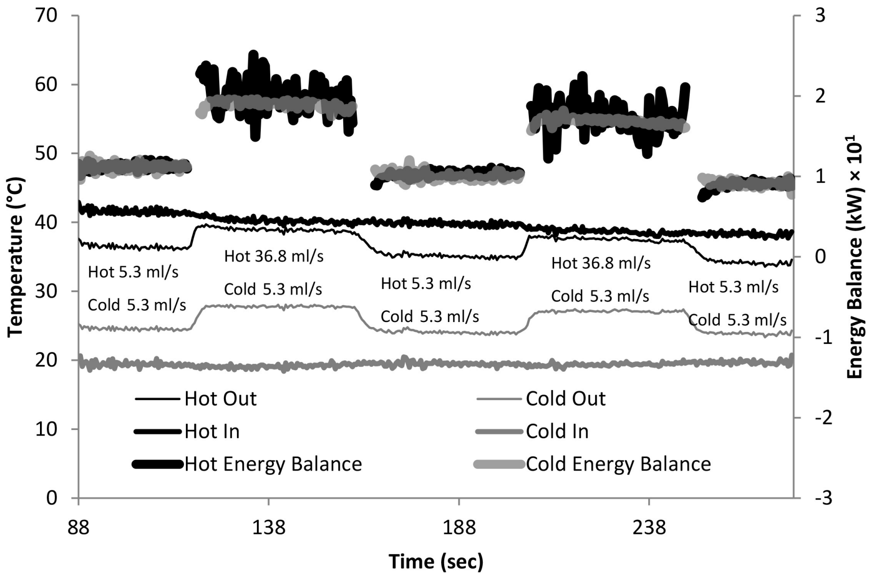

Fig. 6. Graph of typical double pipe temperature and energy duty data as a function of time. Hot water flow was alternated between 5 and 35 GPH (5.3 and 36.8 ml/s), with cold water flow held constant at 5 GPH (5.3 ml/s). Similar data, without the energy duty, for the shell and tube heat exchanger may be found in Coon, et al [15].

simple idealized system, which is desirable. It is more challenging to find the pressure drop correlations that deal with the angles used in the double pipe apparatus, which forces students to practice information literacy skills if predicting this is a desired class activity.

Regarding heat transfer, these systems provide adequate heat exchange for students to observe measurable changes. They can do quick energy balance calculations based on a data set from an instantaneous time point to show qualitative agreement between energy lost by the hot stream and that gained by the cold stream, with the caveat that slightly more heat energy is lost by the hot stream demonstrating loss to the environment. The students can quickly learn the difference between experimental energy balance heat duty and that predicted by a correlation based on heat transfer coefficients, the exchanger area, and the log mean temperature difference. The remarkable aspect of these miniaturized systems is the agreement between heat duties determined by correlations developed for industrial scale equipment and the experimentally measured value even given that a significant amount of heat is lost to the environment because of the lack of insulation.

These exchangers also challenge the intuition of both students and faculty. For example, if one looks just at the temperature trends in Fig. 4, for a double pipe heat exchanger, the data look incorrect, challenging us to ask, "how can we change flow rates and have both hot and cold-side temperatures moving in the same direction?" An analysis based on a set of simple energy balances ($Q = mC_p\Delta T$) can be used to answer this question; the students begin to realize the energy flux is related to the flow rate as well as the temperature change. As the hot-side fluid is increased in flow rate from 5.3 to 36.8 ml/s, though it spends less time in the system and therefore decreases in temperature by a lesser amount, i.e., by 1.2 for the higher versus 5.2 °C for the lower flow rate for example sets of data points, it also has a flow rate 7 times that of the first case and therefore may transfer a greater net amount of heat energy to the cold-side fluid, thereby raising the cold-side temperature, in this case by 8.8 °C compared to the 5.1 °C for the initial 5.3 ml/s hot-side flow rate. Of similar importance is the rationale for the increased heat transfer rate by ~70% for the increased hot-side flow rate. This of course will relate both to an increase in the ΔT_{LM} driving force from the hot to the cold fluid, and the enhanced hot side heat transfer coefficient due to operation at a higher Reynolds number which can be calculated by students using a Nusselt number correlation to confirm that the enhanced heat transfer effect is indeed tied to fundamental concepts.

The temperature data, like most real systems, is also noisy, as can be seen in Fig. 6, which was selected primarily for its comparatively quiet temperature data. This aside, the systems respond quickly, allowing many brief experiments to be run within a short window of time. Though the system can come to a new pseudo steady state in a brief 10 s, student groups are likely to take more time than that to run an experiment. In our experience, students can run a series of three experiments in a five to ten-minute time span.

Finally, we need to discuss prospective system improvements. A possible upgrade for the shell and tube system would be interchangeable tube bundles made from other materials such as stainless steel, with varying tube sizes, numbers of passes, and baffle arrangements. Similarly, the double pipe system could benefit from interchangeable tubing, where sizes, materials, and annular spaces could be easily altered. In both systems, the ability to compare clean new copper tube systems with those having oxidized surfaces and scale deposits would be beneficial. Methods for introducing visualization of flow and temperature boundary layers would also be of interest. Ideally, an instructor can imagine and construct a host of system alterations that will be of benefit to student learning.

3.3 Extended Area Heat Exchanger

The extended area heat transfer unit consists of a radiator and fan. This is built into a chassis to connect to the base unit, Fig. 2. Table A-3 contains the dimensions, flow rate ranges, and heat transfer ranges for this cartridge when operated using hot tap water. This cartridge takes advantage of readily available equipment intended for water-cooling computers. The primary functional parts of the unit consist of a Zalman model ZF8015ATM 2.9 in. (7.4 cm) diameter fan and a radiator with a similar 3 in. (7.6 cm) square of exposed fins with a 1.25 in. (2.9 cm) width. A discussion of the thermal performance of this system may be found in Abdul et al.[7].

3.3.1 System pressure drop

As with the other heat exchangers discussed above, the pressure drop measurements for this system agree with theoretical predictions based on friction losses in smooth, parallel, rectangular channels. Fig. 5 includes a comparison of theoretical and measured pressure drops for this cartridge. As can be seen, the pressure drop measurements follow the same curve as that for the theoretical values and errors, though ranging from 0.2 to 171%, are all within experimental error with the larger values due to the high uncertainty in flow measurement in the low range.

3.3.2 Implications for education and improvement

As with the other cartridges, the extended area heat exchanger offers important learning experiences. It provides an opportunity to discuss the concept of controlling resistances. Theoretical heat transfer coefficients only vary by 0.7% over the 5–44 GPH (5.3–46.3 ml/s) water flow range for the system. This is a clear indication that the air-side resistances control the heat transfer for this unit.

Measuring the temperatures and flowrates on the air-side provides a demonstration on the importance of carefully taking and averaging multiple measurements. This is the norm for stack gas testing, and thus has potential impacts on students' future careers. Beyond simply providing an example of needing multiple measurements, the geometry of the fans and radiators provide an opportunity to learn about the need to carefully choose measurement points. Measurements overlapping the center hub and corners of the square radiator outside the circular-shaped fan produce areas of much lower flow rate. Measurements taken in these areas will not be representative of the system's behavior. Students will have an opportunity to directly see how the quality of their measurements affects their calculations.

As both the water and air-side flow channels are non-circular, students gain experience in dealing with this complication. A non-circular heat flow path down the fins further complicates this. While the double pipe heat exchanger provides a non-circular cross section in the annular region, concentric circles are a simple case. The extended area heat exchanger provides both rectangular and triangular cross sections. This can be used to emphasize the meaning of the hydraulic radius and equivalent diameter by giving multiple, varied examples.

Beyond this, we expect that students will better learn why it is necessary to account for fin effectiveness as they see the fins protruding from the wall and can be prompted to discuss the temperature profile along the fin realizing the temperature at the center deviates significantly from that at the wall. By visual inspection they realize the importance and the how-to's of calculating bare wall and fin areas. By like manner they can understand the rationale for taking a half fin length in determining the x-axis parameter for the fin effectiveness as there exists an adiabatic wall at the center of the fin since heat energy travels down a temperature gradient and that temperature is at a minimum at the fin's center. Even more importantly they can understand the parameters of importance to fin effectiveness as the longer the fin the more temperatures are reduced as heat is conducted down the fin away from the wall to a midpoint equidistant from two successive walls where heat transfer is reduced because of a smaller metal to air temperature gradient. At the same time a higher thermal conductivity of the metal will increase the temperature at the center thereby increasing fin effectiveness.

There's also much to be learned by observing the inlet and outlet water temperatures as a function of

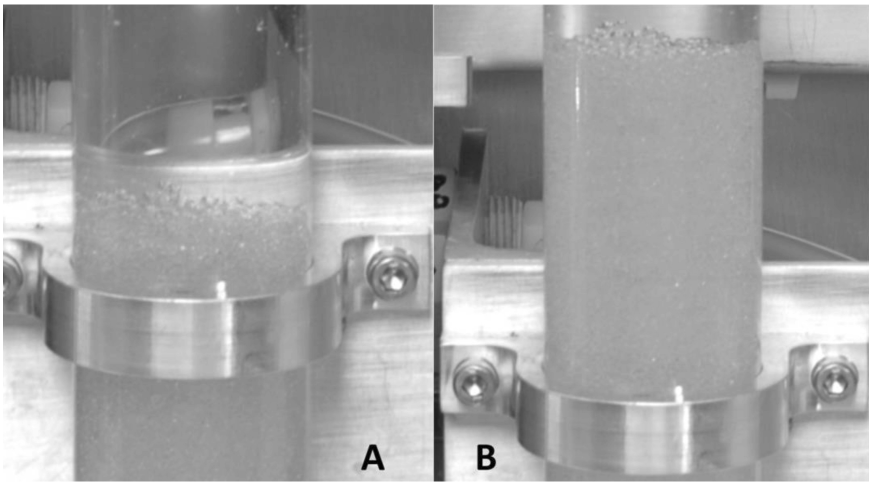

Fig. 7. The Packed/Fluidized bed in operation. Side A shows packed bed operation. Side B shows fluidized operation; note the increase in bed height.

time and when turning off the fan, as was done in the work by Abdul et al. [7]. Students learn an alternate non-steady state batch process method of performing an energy balance, that of taking the drop-in temperature of the water in the reservoir over a period of time and calculating an average heat duty. When observing the area available from the tube walls alone and finding that a low heat transfer coefficient is calculated solidifies the importance of forced convection over extended areas substantiating the utility for fin heat exchangers where heat is to be removed using fluids such as gasses with low thermal conductivities.

3.4 Packed/fluidized bed

The packed and fluidized bed cartridge consists of a 7 in (17.78 cm) vertical pipe with a fine screen at the top and bottom to contain the packing material. At low flow rates or with denser particles fluid flows into the bottom and passes through the bed of particles with packed bed behavior. Fluidized bed behavior is exhibited at higher flow rates or with lower density particles. The cartridge is pictured in Fig. 2, with a measured void fraction for the packed bed found to be 0.33 and dimensions and operating ranges may be found in Table A-4. A closer view of fluidization behavior may be seen in Fig. 7.

3.4.1 Implications for education and improvement

Figure 8 shows a comparison of measured data to theoretical values predicted using the Ergun equation for the linearly increasing pressure drop packed bed regime. The break point between a steep increase in pressure drop and an essentially flat

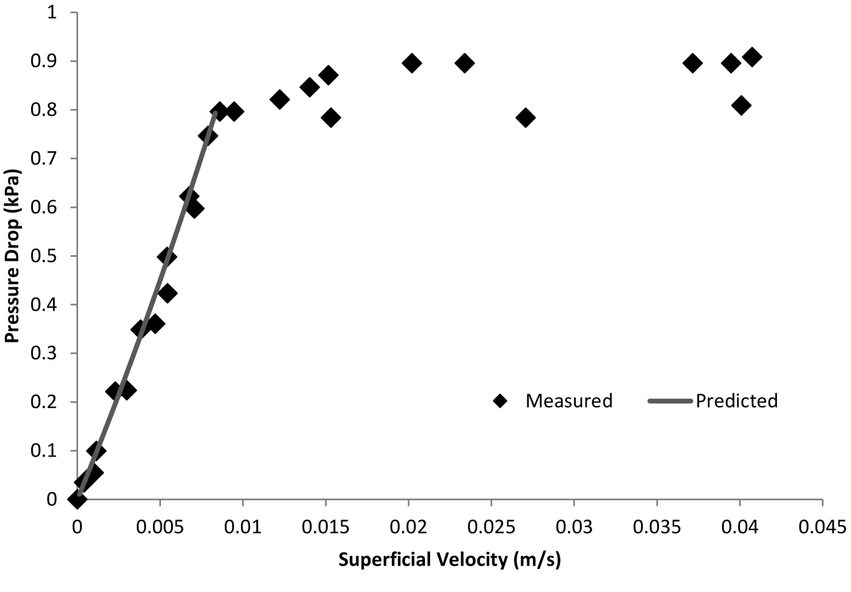

Fig. 8. Comparison of experimentally measured pressure loss as a function of superficial velocity versus correlation predicted values. Packed bed void fraction = 0.33.

pressure drop where fluidization begins is clearly visible. Then the Ergun equation may also be used for determining bed porosity as a function of superficial velocity once fluidization begins. Students can do a force balance on the beads in the bed to determine the pressure drop across required to support the entire fluidized bed.

3.5 Further implications

We also note that the DLMs may be used in a laboratory setting, which in fact has been done at some beta sites [15], it may be desirable to take online data. For this case it may be advisable for an instructor to expect student laboratory teams to address anomalies observed in data collection by proposing explanations for the behavior and determining means for compensating for data irregularities—in fact many of us in the profession assert that these types of problems are the norm in industry and the DLM and data acquisition system present a quality learning tool for exposing students to real world problems they will encounter throughout their careers.

DLMs have also been implemented in an intensive, in-between semester Sophomore course intended to help students develop a more intuitive understanding. Details on this implementation may be found in Abdul, et al.'s 2011 paper [18]. DLMs were a vital part of the motivational gains seen in this study.

4. Student response

Student feedback on how DLM implementation is received is important, and, while it does not replace or eliminate the need for rigorous assessment on how DLMs impact learning, it is a vital component to a successful implementation and provides a mechanism to attain student buy-in and cooperation. In this study students taking our required junior level fluid mechanics and heat transfer course were introduced to the DLMs. However, this course included cooperative (peer teaching), hands-on, active, problem based, and project driven learning with only about 10% lecture. Though the DLMs were just one facet of the learning environment, they provided a central activity that tied the various pedagogies together. While the complexity of the implementation makes it difficult to tease out student responses to just the DLMs, insight is gained by examining student responses to the following open-ended survey questions: "*Please list the course activities that were MOST helpful and why*"; "*Please list the course activities that were LEAST helpful and why*"; "*Would it have been useful to have similar activities in other courses you have taken before and why*"; and finally "*Please provide feedback . . . on anything else you would like us to know about your experiences in this course.*"

The responses were analyzed and coded by subject. Within a subject, responses are categorized as broadly positive, the students felt this type of activity helped them learn, or broadly negative, the students felt this type of activity either did not help or hindered their learning. Table 1 contains a subset of this data selected to indicate how students responded to the various teaching methods used. The data in this table was obtained over two semesters. In all 13 students took the survey the first semester, 11 of which provided written comments. The second semester 39 students took the survey and 30 provided written comments. From this data, we can infer that students found the projects, with 18 positive and 3 negative responses, and what lectures there were, with 14 positive and 2 negative responses, to be helpful. In contrast response to the cooperative learning elements of the course, was neutral with 9 positive and 9 negative responses, and the peer teaching worksheets, with 3 positive and 11 negative comments, were deemed by the students overall as not helpful to their learning.

Focusing exclusively on comments about the hands-on aspects, Table 1 row 2, which consisted solely of DLM activities, if one simply sums the numbers across this row, the results are slightly positive, with 10 positive and 8 negative comments. However, one must also consider the last two rows of Table 1, which contain data for categories that help explain the students' reaction to the DLMs, and provide some helpful insight about their responses. First of all, the majority, in total 18 responses, indicated the DLMs would have been more helpful with modified implementation or if these early prototypes were always working as intended. Written statements corroborate this. For example, in response to the question regarding the most helpful course activities, one student wrote: "*Using the hands-on models in class (when they were working)*". This comment, broadly speaking, was positive. It also falls under the narrower category of 'DLMs not working'. Similarly, one student wrote, in response to the least helpful course activities, "*Working to gather data from the DLM's in class didn't seem that useful, there wasn't enough time and it seemed to hamper learning. Perhaps if there was a separate lab time where DLM work was the only focus this would help.*" While this comment was, overall, negative towards the DLMs, it is clear that this is due to the implementation rather than being a statement about the intrinsic value of the DLMs. A minority of responses, 10 out of a total of 88 from all questions, felt more lecture would have been better.

Table 1. Analysis of a subset of student comments focused on general reaction to classroom teaching methods with a smaller set providing specifics on the DLMs

	Year 1 – 11 of 13 commenting				**Year 2 – 30 of 39 commenting**			
Question (responses positive/negative (+/-)	**Most helpful**	**Least helpful**	**Useful elsewhere**	**Anything else**	**Most helpful**	**Least helpful**	**Useful elsewhere**	**Anything else**
Project +/-	6/0	0/0	1/0	0/0	10/0	0/3	0/0	1/0
Hands-on / DLMs +/-	1/0	1/1	1/0	0/0	4/0	2/6	1/1	0/0
Cooperative learning +/-	2/1	0/1	1/1	0/0	3/0	0/5	3/0	1/1
Lectures +/-	4/0	0/0	0/0	0/0	8/0	1/2	1/0	0/0
Worksheets +/-	0/0	0/4	0/1	0/0	3/1	0/5	0/0	0/0
Subcategories								
Want more lectures	1	0	2	1	0	2	3	1
DLM not working					1	3		
Poor DLM implementation	3		1		1	5	4	1

It is interesting to note that there were very few comments, only two overall, indicating the DLMs did not have a place in the course. It is implementation issues and robustness, specifically the electronics associated with thermocouples and pressure transducers suffering from weak connections, issues typical in beta phase development, that are the source of these concerns. This is true in the current survey data set as well as in surveys conducted in other implementations.

Since the focus in this paper is on the suitability of miniaturized hardware for learning course content, a more detailed analysis will be incorporated into a forthcoming paper on evaluation of student responses to hands-on and active learning on a topic-by-topic basis. We will state, however, that in the years such surveys were implemented, the DLMs were used to replace lecture almost entirely. In light of the fact that this teaching methodology sharply contrasts the predominantly lecture-based mode of instruction, it is perhaps unsurprising that the students were not as enthusiastic overall about the implementation. The sample quote about wanting a separate lab time is representative in that many students, year-by-year, uniformly request more lecture to go along with or precede the DLM experience. In summary if we ignore the comments about implementation rather than the usefulness of the DLMs themselves, and once the electronics reliability problems are addressed, students perceive the DLMs as a useful addition.

We highlight once more that the DLMs were implemented in a context of a cooperative semester-long team project-based learning environment. The intention on the part of the instructor was to use the DLMs to motivate learning by making each individual team member responsible for a major set of concepts associated with a different DLM cartridge and a companion worksheet-based guided inquiry. The intention was to use the DLMs to foster thoughts on how similar processes could be used in team design projects, though usually on a larger scale. The complexity of this implementation makes it difficult to ascertain, when the majority of the students cite the project-based learning as the most helpful, whether or not the student teams benefitted from the instructor's intent, i.e. the DLMs informing project efforts, without specifically asking them about this, a question to be asked in future implementations.

4.1 DLM implementation

DLM implementation does come with some resource costs. DLMs are best utilized in a classroom space which has some sort of level table surface. They do require a small amount of time before and after class to set up and take down. They also need either carts for transport to and from the classroom or storage within the classroom. Buckets will be needed to transport hot or cold tap water to and from the classroom. In addition, mops and some form of toweling are required to deal with the inevitable small spills. In terms of technician time, the non-electronic components of the DLMs are now robust and do not require specialized maintenance. The electronics however, were proven to be intermittently unreliable in the state that existed at the time of the rigorous model and experimental comparisons which are the subject of this paper. This problem is more recently addressed in a commercial DLMX model now available through Armfield Ltd. and is expected to be less of an issue going forward. Now that electronics issues have been addressed for such systems, maintenance consists of ensuring the cartridges and units are drained well, charging or replacing the batteries, and occasionally replacing a faulty circuit board. Beyond these currently minimal maintenance issues what is important to know is that DLMs are reliable as unique hands-on learning systems allowing visualization of the internal workings of common industrial equipment and the correlations developed for industrial-sized equipment may be applied by students to cement learning of the concepts associated with the design of this equipment.

DLMs were developed for a class that has ranged from approximately 15 to 40 students over the period of development. The extent to which they have been used in class has varied significantly over the time they have been developed. In addition, DLM's have been implemented in a class of approximately 170 students at Ahmadu Bello University in Zaria Nigeria. DLM use has been concurrent with other pedagogical interventions. It has functioned as an enabling technology, allowing the instructor to implement, for example, a highly structured cooperative learning environment involving hands-on learning. As such the specific impact of DLM implementation has been difficult to isolate. Determining the impact of DLM implementation has been a recent focus of our group's research.

5. Conclusions

Based on the performance data presented, DLMs are a qualified success. They are small enough to be transported easily using carts, and will fit on most student desks though not those with a swing-arm. They have also been used in unit operations laboratories though improvements could be added including replacement of rotameters with electronic flow meters to reduce measurement errors. For classroom use though, the rotameters are useful for understanding uncertainties and error propagation. Reaching turbulent flow conditions has been met with difficulty with the units, something which could be improved upon with alternative pumps and/or by reducing pressure losses. With regard to heat transfer characteristics, the DLM can operate and give meaningful data using just hot and cold tap water. Furthermore, the heat transfer units respond quickly, reaching pseudo-steady state in less than 30 seconds so students may perform multiple experiments within a five to ten minute window. This allows multiple groups to use the same piece of equipment within a single class period. Pressure drops and heat transfer coefficients generally agree well with correlations for industrial sized equipment and system trends with changing flow rates and temperatures are as expected offering many insights helpful for learning fluid mechanics and heat transfer. There are anomalous and counterintuitive things that occur as well, including rather noisy data. This provides opportunities for students to struggle with experimental realities and develop a more thorough understanding of the phenomenon they are observing. Because of the generally positive student responses it is beneficial to continue development of such systems making sure more reliable electronics, additional lectures, and/or separate lab times are considered to improve the DLM experience.

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References

1. P. B. Golter, B. J. Van Wie, P. V. Scuderi, T. W. Henderson, R. M. Dueben, G. R. Brown and W. J. Thomson, Combining Modern Learning Pedagogies in Fluid Mechanics and Heat Transfer, *Chemical Engineering Education*, **39**(4), 2005, pp. 280–287.
2. G. Kaletunc, K. Duemmel and C. Gecik, Teaching Process Engineering Using an Ice Cream Maker, *Chemical Engineering Education*, **41**(2), 2007, pp. 131–136.
3. K. L. Hohn, The Chemical Engineering Behind How Pop Goes Flat: A Hands-on Experiment for Freshmen, *Chemical Engineering Education*, **41**(1), 2007, pp. 14–18.
4. M. E. Sad, M. R. Sad, A. A. Castro and T. F. Garetto, Chemical Kinetics, Heat Transfer and Sensor Dynamics Revisited in a Simple Experiment, *Chemical Engineering Education*, **42**(1), 2008, pp. 17–22.
5. A. R. Minerick, Versatile Desktop Experiment Module (DEMo) on Heat Transfer, *Chemical Engineering Education*, **44**(4), 2010, pp. 274–279.
6. J. S. Condoret, Teaching Transport Phenomena around a Cup of Coffee, *Chemical Engineering Education*, **41**(2), 2007, pp. 137–143.
7. B. Abdul, B. J. Van Wie, J. T. Babauta, P. B. Golter, G. R. Brown, R. B. Bako, A. S. Ahmed, E. G. Shide, F. O. Anafi and O. O. Olaofe, Addressing Student Learning Barriers in Developing Nations with a Novel Hands-on Active Pedagogy and Miniaturized Industrial Process Equipment: The Case for Nigeria, *International Journal of Engineering Education*, **27**(2), 2011, pp. 458–476.
8. P. B. Golter, Y. Jiang, D. B. Thiessen, B. J. Van Wie, G. R. Brown and N. Yurt-Beyenal. Developing, Implementing and Assessing Desktop Scale Engineering Laboratory Apparatus, *Global Colloquium on Engineering Education*, Cape Town, South Africa, 2008.
9. P. Golter, B. Van Wie, G. Held and J. Windsor, Practical Considerations for Miniaturized Hands-on Learning Stations, *Annual Conference of the American Society for Engineering Education*, Chicago, IL, 2006.
10. P. B. Golter and B. J. Van Wie, Desktop Learning Module Implementation, *Annual Conference of the American Society for Engineering Education*, 2007.
11. N. Yurt, P. B. Golter, B. J. Van Wie, G. R. Brown and D. Thiessen, Extending Desktop Learning Modules beyond Traditional Chemical Engineering, *Annual Conference of the American Society for Engineering Education*, Pittsburg, PA, 2008.
12. B. J. Van Wie, P. B. Golter, G. R. Brown, J. Babauta, R. Bako, B. Abdul, A. Ahmed, E. Shide and F. Anafi, Internationalizing Modern Pedagogies with the Aid of Desktop

Learning Modules in Engineering Classrooms, *Global Colloquium for Engineering Education*, Cape Town, South Africa, 2008.

13. W. D. Schlecht, P. B. Golter, J. C. Adam, R. F. Richards, P. Dutta, D. C. Davis, O. O. Adesope, J. D. Law, E. P. Maurer, M. J. Pitts, D. B. Thiessen, G. R. Brown, M. D. Compere and B. J. Van Wie. Multi-Disciplinary Project-Based Paradigm that Uses Hands-on Desktop Learning Modules and Modern Learning Pedagogies, *Annual Conference of the American Society for Engineering Education*, Vancouver, BC, 2011.
14. P. B. Golter, B. J. Van Wie and G. R. Brown, Comparing Student Experiences and Growth in a Cooperative, Hands-on, Active, Problem-Based Learning Environment to an Active, Problem-Based Environment, *Annual Conference of the American Society for Engineering Education*, Honolulu, HI, 2007.
15. L. B. Coon, P. B. Golter, D. B. Thiessen, O. O. Adesope and B. J. Van Wie, Unit Operations Lab Bazaar: Assessment of Miniature Industrial Equipment, *Annual Conference of the American Society for Engineering Education*, Vancouver, BC, 2011.
16. N. Yurt-Beyenal, C. Poor, B. J. Van Wie, G. Brown, P. B. Golter and D. Thiessen, Miniature Open Channel Weir for the Standard Classroom—Implementation and Assessment, *Annual Conference of the American Society for Engineering Education*, Austin, TX, 2009.
17. A. W. Chickering and Z. F. Gamson, Seven Principles for Good Practice in Undergraduate Education, *AAHE Bulletin*, **39,** 1987, pp. 3–7.
18. B. Abdul, E. A. O'Rear, G. R. Brown, P. B. Golter, D. B. Thiessen and B. J. Van Wie, Experience with an Intensive, Hands-on Pre-Transport Course, *Annual Conference of the American Society for Engineering Education*, Vancouver, B.C., 2011.
19. B. Abdul, D. B. Thiessen, B. J. Van Wie, G. R. Brown and O. O. Adesope. Development and Deployment of a Rubric Based on Fink's Cognitive Dimensions in a Fluid Mechanics and Heat Transfer Class with Potential Applications in a Variety of Engineering Classes, *Annual Conference of the American Society for Engineering Education*, San Antonio, TX, 2012.
20. B. Abdul, B. J. Van Wie, E. G. Shide, F. O. Anafi, A. S. Ahmed and G. R. Brown, An Evaluation of Pedagogical Gains in a Fluid Flow Class When Using Desktop Learning Modules in an African University, *Annual Conference of the American Society for Engineering Education*, Austin, TX, 2009.
21. J. K. Burgher, D. Finkel, D. B. Thiessen, B. J. Van Wie and O. Adesope, New Hands-on Fluid Mechanics Cartridges and Pedagogical Assessment, *Annual Conference of the American Society for Engineering Education*, Atlanta, GA, 2013.
22. J. K. Burgher, D. Finkel, B. J. Van Wie and O. Adesope, Comparing Misconceptions in Fluid Mechanics Using Interview Analysis Pre and Post Hands-on Learning Module Treatment, *Annual Conference of the American Society for Engineering Education*, Indianapolis, IN, 2014.
23. P. B. Golter, G. Brown, B. J. Van Wie and D. Thiessen, Adoption of a Non-Lecture Pedagogy in Chemical Engineering: Insights Gained from Observing an Adopter*, Journal of STEM Education*, **13**(5), 2011.
24. J. Burgher, D. Finkel, O. Adesope and B. Van Wie, Implementing and Assessing Interactive Physical Models in the Fluid Mechanics Classroom, *International Journal of Engineering Education*, **32**(6), 2016, pp. 2501–2016.
25. B. Abdul, O. Adesope, D. Thiessen and B. Van Wie, Comparing the Effects of Two Active Learning Approaches in an Engineering Education Classroom, *International Journal of Engineering Education*, **32**(2), 2016, pp. 654–669.
26. X. Li and B. Van Wie, Hands-on Tabletop Units for Addressing Persistent Conceptual Difficulties in Continuity and Frictional Loss in Fluid Mechanics*, Journal of STEM Education*, **17**(3), 2016, pp. 47–54.
27. N. Hunsu, B. Abdul, B. Van Wie, O. Adesope and G. Brown, Exploring Students' Perceptions of an Innovative Active Learning Paradigm in a Fluid Mechanics and Heat Transfer Course*, International Journal of Engineering Education*, **31**(5), 2015, pp. 1200–1213.
28. J. K. Burgher, D. B. Thiessen, B. J. Van Wie, A. Arasteh, D. Finkel, B. Abdul and B. E. Eaton, *Desktop Learning Modules for Fluid Mechanics and Heat Transfer Classroom Workbook: User's Manual, Worksheet Exercises and Assessments*, WSU Publications, Pullman, WA, 2013.
29. S. Brown, A. Easley, D. Montfort, J. Adam, B. Van Wie, O. Adesope, C. Poor, C. Tobin and A. Flatt, Effectiveness of an Interactive Learning Environment Utilizing a Physical Model, *Journal of Professional Issues in Engineering Education and Practice*, **140**(3), 2014, pp. 04014001-1-10.
30. D. Kolb, *Experiential Learning*, Prentice-Hall, Englewood Cliffs, NJ, 1984.
31. D. A. Kolb and L. H. Lewis, *Facilitating Experiential Learning: Observations and Reflections*, Jossey-Bass, San Francisco, 1986.
32. M. T. H. Chi and R. Wylie, The ICAP Framework: Linking Cognitive Engagement to Active Learning Outcomes, *Educational Psychologist*, **94**(4), 2014, pp. 219–243.
33. M. T. H. Chi, P. J. Feltovich and R. Glaser, Categorization and Representation of Physics Problems by Experts and Novices, *Cognitive Science*, **5**, 1981, pp. 121–152.
34. C. J. Atman, D. A. Adams, M. E. Cardella, J. Turns, S. Mosborg and J. Saleem, Engineering Design Processes: A Comparison of Students and Expert Practitioners, *Journal of Engeeering Education*, **96**(4), 2007, pp. 359–379.
35. P. A. Kirschner, Cognitive Load Theory: Implications of Cognitive Load Theory on the Design of Learning, *Learning and Instruction*, **12**(1), 2002, pp. 1–10.
36. O. O. Adesope, N. Hunsu and B. J. Van Wie. The Effects of Using Desktop Learning Modules on Engineering Students' Motivation: A Work in Progress, *Annual Conference of the American Society for Engineering Education*, Seattle, WA, 2015.
37. D. A. Donohue, Heat Transfer and Pressure Drop in Heat Exchangers, *Industrial and Engineering Chemistry*, **41**(11), 1949, pp. 2499–2511.
38. R. H. Perry, D. W. Green and J. O. Maloney, *Perry's Chemical Engineers' Handbook*, McGraw-Hill, 1984.

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Appendices

Table A-1. Dimensions and operating ranges – venturi / Reynolds experiment and orifice experiment

		Venturi		**Orifice**	
Diameter		0.25 in.	6.35 mm	0.25 in.	6.35 mm
Overall Length		13.1 in.	33.3 cm	13.1 in.	33.3 cm
Overall	Actual	0.1 – 30 in. H_20	0.025 – 7.5 kPa	2 – 82 in. H_20	0.5 – 20.4 kPa
ΔP	Theoretical	0 – 40 in. H_20	0 – 9.96 kPa	0 – 85 in. H_20	0 – 21.2 kPa
Throat / Orifice Diameter		0.16 in.	4.1 mm	0.125 in.	3.2 mm
Diameter Ratio (β)		0.64		0.5	
Coefficient (C_v / C_o) (textbook)		1.09 (0.98)		0.63 (0.61)	
Flow Rate		5 – 50 GPH	7 – 52.5 ml/s	5 – 37.5 GPH	7 – 39.4 ml/s
Re Approaching the Meter		1600 – 12,300		1600 – 9200	
Meter	Actual	0 – 20 in. H_20	0 – 5.0 kPa	2 – 106 in. H_20	0.5 – 26.4 kPa
ΔP	Theoretical	0.1 - 12 in. H_20	0.025 – 3.0 kPa	2 – 120 in. H_20	0.5 – 29.9 kPa
Manometer Section Diameter		0.3125 in.	7.9 mm		
Manometer Section Length		5.125 in.	13 cm		
Re in Manometer Section		1300 – 9900			

Table A-2. Dimensions and operating ranges for the shell and tube and double pipe heat exchangers

		Shell and Tube		**Double Pipe**	
		(English)	**(Metric)**	**(English)**	**(Metric)**
Tube Bundle Length		6 in.	15.2 cm	12 in.	30.5 cm
Curve Dimensions				0.36 in. (9.1 mm) radius @ 18.6° angle	
Tube / Inner Pipe Inner Dia.		0.0625 in.	1.59 mm	0.0625 in.	1.59 mm
Tube / Inner Pipe Outer Dia.		0.125 in.	3.18 mm	0.125 in.	3.18 mm
Shell / Outer Pipe Dia.		1.25 in.	3.18 cm	0.25 in.	6.35 mm
Passes		1 Shell, 2 Tube			
Baffle Window		20%			
Baffle Pitch (in.)		0.83 in	2.11 cm		
Tube Arrangement		12 per pass, triangular pitch			
Tube Pitch (in.)		0.16 in.	4.06 mm		
Inner Flow Range		10 – 45 GPH	10.5 – 47.3 ml/s	5 – 10 GPH	5.3 – 10.5 ml/s
Shell / Annulus Flow Range		10 – 40 GPH	10.5 – 42.0 ml/s	5 – 33 GPH	5.3 – 34.7 ml/s
Re Range (tube / inner pipe)		600 – 3800		500 – 3000	
Re Range (shell / annulus)		140 – 1200		700 – 8000	
Tube / Inner Pipe ΔP	Actual	2 – 55 in. H_2O	0.5 – 13.7 kPa	109 – 170 in. H_2O	27.2 – 42.3 kPa
	Theoretical	1 – 50 in. H_2O	0.25 – 12.5 kPa	15 – 70 in. H_2O	3.74 – 17.4 kPa
Shell / Annulus ΔP	Actual	0 – 2 in. H_2O	0 – 0.5 kPa	10 – 70 in. H_2O	2.5 – 17.4 kPa
	Theoretical	0 – 3 in. H_2O	0 – 0.75 kPa	5 – 125 in. H_2O	1.25 – 31.1 kPa
Cold Temperature		61 °F	16.1 °C	58 °F	14.4 °C
Hot Temperature		117 °F	47.2 °C	119 °F	48.3 °C
Heat Transfer	Actual	500 – 4000 BTU/hr	146 – 1170 J/s	500 – 1000 BTU/hr	146 – 293 J/s
Range	Theoretical	1700 – 5500 BTU/hr	498 – 1610 J/s	980 – 1400 BTU/hr	287 – 410 J/s
Time to pseudo-steady state		8.6 ± 1.6 s		10.3 ± 1.5 s	

Table A-3. Dimensions and operating ranges for the extended area heat exchanger

		English	Metric
Tube Size		3.12 x 0.075 x 1.125 in.	7.92 x 0.19 x 2.86 cm
Fin Spacing		1/16 in.	0.159 cm
Total Fin Length		5/16 in.	0.794 cm
Number of Tubes		8	
Fin Material		Copper	
Water Flow Range		5 – 44 GPH	5.3 – 46.2 ml/s
Air Velocity		3.3 ft/s	1.01 m/s
Pressure Drop Range	Actual	0.3 – 9.1 in. H_2O	0.075 – 2.27 kPa
	Theoretical	0.2 – 8.4 in. H_2O	0.05 – 2.09 kPa

Table A-4. Packed/Fluidized bed dimensions and operating ranges

		English	Metric
Bed Height, Maximum		7 in.	17.8 cm
Bed Diameter		1.25 in.	3.18 cm
Initial Packing Depth		2.75 in.	6.99 cm
Packing Diameter		0.03 – 0.05 (0.04 avg.) in.	0.76 – 1.3 (1.0 avg.) mm
Packing Type		Borosilicate Glass Beads	
Void Fraction		0.33	
Packing Density		156 lb/ft^3	2500 kg/m^3
Flow Range, Packed		0 – 4.5 GPH	0 – 4.73 ml/s
Flow Range, Fluidized		4.5 – 20 GPH	4.73 – 21.0 ml/s
Fluidization Velocity		0.02 ft/s	0.0061 m/s
ΔP Range	Packed	0 – 3.2 in H_2O	0 – 0.797 kPa
	Minimum Fluidization	3.2 in H_2O	0.797 kPa
	Fluidized	3.2 – 3.6 in H_2O	0.797 – 0.897 kPa