Miniaturized Inexpensive Hands-On Fluid Mechanics Laboratory Kits for Remote On-Line Learning

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Dr. Matthew J. Traum, Engineer Inc

Dr. Matthew J. Traum is founding CEO at Engineer Inc (www.EngineerInc.net), an engineering education start-up. Traum invented @HOLM™ lab kits to enable students in on-line courses to build and run engineering experiments remotely at home.

Before founding Engineer Inc, Dr. Traum was a well-known higher education administrator, fund raiser, educator, and researcher with co-authorship of 11 peer-reviewed research journal articles, 15 refereed research conference articles, and 17 refereed pedagogical conference articles. As a PI or Co-PI, Traum has attracted over $800 K in funding for research, education, and entrepreneurial ventures from multiple sources including NSF, NASA, ASHRAE, the Texas State Energy Conservation Office, and several industry sponsors.

Most recently as Associate Professor and Director of Engineering Programs at Philadelphia University, Dr. Traum led the Mechanical Engineering Program through a successful ABET interim visit resulting in no deficiencies, weaknesses, or concerns.

Previously, Dr. Traum was an assistant professor at the Milwaukee School of Engineering (MSOE), one of the top-ten undergraduate-serving engineering universities in the U.S. Dr. Traum coordinated MSOE's first crowd-funded senior design project. He also co-founded with students EASENET, a start-up renewable energy company to commercialize waste-to-energy biomass processors.

Dr. Traum began his academic career as a founding faculty member in the Mechanical & Energy Engineering Department at the University of North Texas - Denton where he established a successful, externally-funded researcher incubator that trained undergraduates to perform experimental research and encouraged matriculation to graduate school.

Traum received a Ph.D. in mechanical engineering from the Massachusetts Institute of Technology where he held a research assistantship at MIT's Institute for Soldier Nanotechnologies. At MIT he invented a

new nano-enabled garment to provide simultaneous ballistic and thermal protection to infantry soldiers. Dr. Traum also holds a master's degree in mechanical engineering from MIT with a focus on cryogenics and two bachelor's degrees from the University of California, Irvine: one in mechanical engineering and the second in aerospace engineering. In addition, he attended the University of Bristol, UK as a non-matriculating visiting scholar where he completed an M.Eng thesis in the Department of Aerospace Engineering on low-speed rotorcraft control.

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Abstract

Hands-on laboratory experiments are known to improve student learning in engineering and science. In parallel, the Internet's rise has created new and unprecedented opportunities for remote learning. Development of laboratory experiences completed remotely is the natural blending, extension, and evolution of these two educational phenomena.

We report creation of inexpensive Hands-On Learning Module (*@HOLM*™) fluid mechanics laboratory kits paired with an online undergraduate fluids mechanics course, which can be seamlessly inserted into any ABET-accredited baccalaureate mechanical engineering curriculum. The physical kit is small and inexpensive, enabling it to be shipped to a remote learner who then assembles each experiment, collects data, and performs analysis at his/her location. Kit experiments retain all the features, robustness, and rigor of full-scale brick-and-mortar laboratories.

Here, data collected from one laboratory kit beta-tested with junior and senior mechanical engineering students is used as an example. Analysis of both indirect and direct assessments indicates that learning outcomes are achieved to a very high level. The *@HOLM*™ approach is therefore demonstrated as a viable alternative to conventional brick-and-mortar teaching lab techniques now used by all accredited mechanical engineering Bachelor of Science programs.

This new approach provides the opportunity for mechanical engineering B.S. programs to offer their students rigorous hands-on fluid mechanics lab experiences without need or expense of maintaining physical laboratory spaces and equipment. Additional benefits of on-line instruction; including massively parallel instruction, asynchronous content delivery, and multimedia presentation to address a variety of learning styles; are also enabled by this new approach.

Introduction

Despite the rise of remote education delivered online, including Engineering Master's programs, nowhere does there exist an ABET-accredited undergraduate mechanical engineering program taught exclusively on-line. [1] To understand why, a quote from the Online Engineering Web portal at North Carolina State University (NCSU) is instructive. It states that "because many undergraduate engineering classes have laboratory requirements, [NCSU does] not offer an undergraduate online degree in engineering." [2] While the University of North Dakota claims to offer an online mechanical engineering B.S. degree, it nonetheless still requires remote learners to travel to campus to complete laboratory activities in dedicated college-affiliated brick-and-mortar facilities. [3] We believe insistence that undergraduate mechanical engineering students complete lab experiments at brick-and-mortar facilities is outmoded.

We propose an alternative approach with potential to revolutionize distance undergraduate mechanical engineering education: Hands-On Learning Module (*@HOLM*™) laboratory kits. These kits maintain the centrality of laboratories in the mechanical engineering curriculum while allowing undergraduate engineering courses to be taught fully remotely and on-line. In this new paradigm, remote learners receive in the mail an inexpensive *@HOLM*™ kit containing experiments integrated into the online course they are taking. Following assembly instructions, learners build each apparatus, run experiments, collect and analyze data, and author lab reports. By describing here selected *@HOLM*™ experiments, we show that these exercises are essentially miniaturized versions of larger-scale experiments found in brick-and-mortar engineering teaching laboratories. They function robustly and in the same capacity. Thus, *@HOLM*™ kits address and measure the same learning outcomes typically assessed by conventional lab experiences in brick-and-mortar facilities, and they can facilitate a transition to online education for undergraduate mechanical engineering programs.

Background

Are laboratory experiences required for successful undergraduate engineering education? Blosser summarizes the history of laboratory use in science and engineering education starting from the 19th Century when "laboratory instruction was considered essential because it provided training in observation, supplied detailed information, and aroused pupils' interest." [4] According to Blosser, however, the value of teaching labs was questioned in the 1970's and 1980's by several studies that examined student achievement, attitudes, critical thinking, cognitive style, science understanding, skill development, interest level, retention in courses, and the ability to work independently. Some studies found no significant differences between groups who had lab experiences verses groups that did not. [5] However, in the intervening period of the early 21st Century, numerous reviews and studies (more than can be cited practically here) refuted the late 20th Century view and confirmed that laboratories are an important component of student learning in the sciences and engineering. [6-8]

In their historical description of undergraduate engineering education laboratories, Feisel and Rosa [9] point out that by the 1990's, ABET had established criteria that explicitly required laboratory practice. [10] The later ABET EC2000 criteria did not explicitly require laboratory instruction, but it referred to experiments, use of modern tools, and institutional support. [11] These ABET mandates implied need for teaching labs, and instilled the sense that labs are essential for engineering education. Many engineering programs have therefore institutionalized attainment of the following ABET Criterion 3 Student Outcomes through laboratory experiences:

(b) an ability to design and conduct experiments, as well as to analyze and interpret data
(e) an ability to identify, formulate, and solve engineering problems
(g) an ability to communicate effectively
(k) an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.

As Feisel and Rosa further point out, lack of feasible ways to offer remote lab experiences prior to the Internet made brick-and-mortar laboratory teaching facilities essential. [9] However, even after the Internet became available, inertia instilled in the engineering education community the erroneous belief that laboratory experiences must occur in brick-and-mortar facilities. Despite this inertia, some attempts have been made to create remote laboratory experiences in engineering and the sciences and to evaluate how well students learn from these remote labs. For example, Corter and colleagues explored student achievement of learning objectives using cantilever beam experiments where content was delivered through three different means: 1) hands-on, 2) remote, and 3) simulated. One group of students studied the loading and deflection of a real, physical cantilever beam in a conventional brick-and-mortar laboratory. A second student cohort ran the same experiment, but they performed it via the Internet on an instrumented and remotely-actuated apparatus. The third cohort studied a computer simulation of the deflecting cantilever with no corresponding physical hardware. [12] The researchers found that the remote and computer simulated labs were at least as effective as the traditional brick-and-mortar lab experience. In some cases, students responded positively to the remote lab experiences and performed better under that pedagogy. In a more detailed follow-up study using the same three cantilever experiment delivery methods, Corter and colleagues studied the impacts of remote labs on group dynamics. They found that for in-person labs, student group data collection is more effective than individual data collection whereas this effect is reversed for remotely-operated labs. The researchers also found that students rated remotely-operated labs as less effective than simulated labs; however despite their perceptions, students who had completed remotely-operated labs fared better on tests. [13]

Ma and Nickerson performed an extensive literature review of the pros and cons of hands-on, simulated, and remote laboratories. [14] They found that hands-on lab adherents emphasize importance of design skills. Remote laboratory adherents do not discuss design. They also point out that modern brick-and-mortar laboratory experiments are often mediated by technology. So these labs are just virtual experiments delivered locally.

The only instance we found in the peer-reviewed literature of a STEM instructor sending experiments home to remote learners to cover a full course is the work of Hoxha1 and colleagues. Here the Spartan physical resources of the authors' war-time Albanian chemistry classroom necessitated development of lab experiments students could perform with items acquired from their households. The chemistry class itself was not offered remotely online, but the labs had to be completed by students at home to provide hands-on learning given lack of physical classroom resources. [15]

In a private communication, L. Feisel credits Professor William C. Beston of Broome Community College (now retired) as the first engineering faculty member to conceive of and attempt mailing engineering lab kits to remote learners. [16] However, no additional information on this work was found in the peer reviewed literature. When contacted, Professsor Feisel indicated this work had been absorbed into the online B.S. electrical engineering program at Stony Brook University.

Stony Brook University as well as Arizona State University both achieved ABET accreditation of fully online electrical engineering B.S. degree programs in 2014, proving that brick-and-mortar facilities are not essential to obtain program accreditation through the ABET Engineering Accreditation Commission (EAC). Stony Brook offers the final two years of a four-year degree fully online to remote learners. It recommends that students complete lower division courses (which do include physics and chemistry labs) at local community colleges. [17] This degree program includes two required electrical engineering laboratory courses in which students build and test real circuits with real components using home-based instrument packages and oscilloscopes that plug into personal computers. [18,19]

Apparatus Description and Validation

Several examples in the engineering education literature show instructors using low-cost experimental systems or common household items as laboratory experiments in fluid mechanics

[20] and thermal-fluid-sciences. [21,22] However, none of these instructors used the teaching systems they created to support online courses taught to remote learners.

The fully online engineering fluid mechanics course with *@HOLM*™ laboratories described here is intended to replace a conventional three-semester-credit-hour face-to-face fluid mechanics lecture/laboratory course in any ABET-accredited undergraduate mechanical engineering curriculum. It is designed to be completed in 15 weeks, the typical duration of a one-semester course. As with any conventional for-credit engineering college course, learners are expected to commit at least 12 hours per week. The proposed online class will consist of ten unique sections with two laboratory experiments available for each section. Each course section covers a unique topic within the overall field of Fluid Mechanics consistent with a typical undergraduate course. Depending on the content instructors plan to emphasize in their individual courses, they can select zero, one, or both of the two available experiments for each section to customize their class. The instructor-selected *@HOLM*™ experiments are then packaged and mailed to enrolled remote learners. Table 1 summarizes the course's section topics and associated laboratories.

Table 1: Section and laboratory structure for the Engineer Inc online Fluids Mechanics course with *@HOLM*™ laboratories, showing correlating technical topics and lab exercises. The five experiments preceded by the dagger symbol (†) will be discussed here.

Section 01: Introduction to the Fluid Mechanics Course
Laboratory 00: Lab Safety & Intro to @HOLM™ Exercises
Laboratory 01: Exploring How Pressure Transducers Work
Section 02: Uncertainty Analysis & Dimensional Analysis
Laboratory 02: Experimental Uncertainty Analysis
† Laboratory 03: Non-Dimensionalisation & Similitude
Section 03: Fluid Properties
Laboratory 04: Fluid Properties: Viscosity and Density
Laboratory 05: Pascal's Law & A Hydraulic Lift
Section 04: Hydrostatics & Buoyancy
† Laboratory 06: Hydrostatic Stand Pipe
Laboratory 07: Archimedes Principle & Buoyancy
Section 05: Reynolds Transport Theorem - Integral Analysis
† Laboratory 08: Momentum Conservation & Jet Force
Laboratory 09: Conservation of Rotational Momentum
Section 06: Bernoulli's Equation & Potential Flow
Laboratory 10: Torricelli Fountain
Laboratory 11: Vortex in a Bottle
Section 07: Navier-Stokes Equation - Differential Analysis
Laboratory 12: Flow Transition Laminar-to-Turbulent
† Laboratory 13: Measuring Velocity Profile and Development Length
Section 08: Internal Flows - Viscous Flows in Pipes & Ducts
Laboratory 14: Pipe Flow - Major Losses
Laboratory 15: Minor Losses, Flow Metering, and Pumping Power
Section 09: External Flows - Flow Past Immersed Bodies
Laboratory 16: Drag & the Falling Sphere Viscometer
Laboratory 17: Pitot-Static Probe Velocity Measurement
Section 10: Compressible Flow
† Laboratory 18: Conservation Laws and the Radial Hydraulic Jump

To provide a sense of how the labs function, what data are collected, and what experimental results look like, five *@HOLM*™ fluids experiments are described here. Sample results are given to demonstrate experimental rigor and validity.

Laboratory 03: Non-Dimensionalisation & Similitude
Non-Dimensionalisation and similitude are important applied techniques both for reducing experimental complexity and obtaining meaningful and predictive results from scaled-down models when experiments on full-scale systems are impractical. One type of fluid mechanical apparatus often used for predicting performance of full-scale engineering systems using smaller models is the wind tunnel or water tunnel. However, non-dimensionalisation and similitude are also useful in other areas of fluids mechanics and engineering.

Similitude in engineering occurs when a model and real application share kinematic, dynamic, and geometric similarity. Non-Dimensionalization is the partial or full removal of units from an equation involving physical quantities by a substitution of variables. The equation used for this lab is the Buckingham-Pi theorem, which culminates in the following expression

$$N_{\Pi} = n - k \tag{1}$$

where the number of Pi terms, N_{Π}, is a function of the number of physical variables, n, and the number of independent physical units, k.

In this experiment, students test the notion that non-dimensionalism and similitude can reduce experimental complexity and provide predictive results from scaled-down models when experiments on full-scale systems are impractical.

Students cut four 8.5” X 11” sheets of blank paper into 12 rectangles of arbitrary length and width by cutting each sheet 3 times. They then record and tabulate the area, perimeter, and width of each rectangle created using a ruler for measurement. For the report, students plot the area of each rectangle as a function of its perimeter. Using a spreadsheet plotting tool they determine the R^2 value of the best-fit quadratic curve running through the data.

To develop the theory describing what the experimental curve should look like, students apply the steps of the Buckingham-Pi process, learned in the online lecture portion of the course, to reveal the functional relationship between the Pi terms. They should find a quadratic relationship between dimensionless terms representing the areas and perimeters of the small cut rectangles. Figure 1 shows a Monte Carlo simulation of 120 rectangles (100 times the number generated by each individual student in their experiments) demonstrating how a result would appear over a massive number of measurements. In their experiment, students will

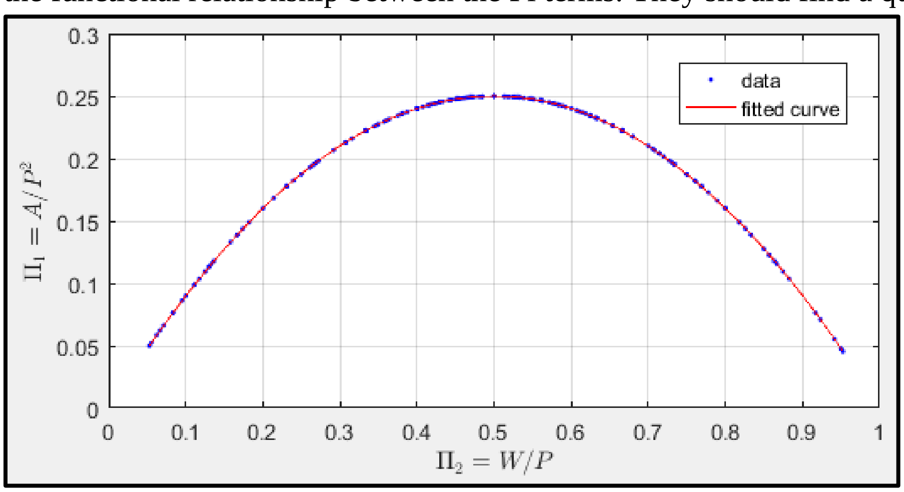

Figure 1: Monte Carlo simulation of paper cutting dimensional analysis exercise shows a parabolic relationship between Pi terms.

produce only 12 of the experimental dots in Figure 1, but the result should be consistent – the data fall on a parabolic curve.

To further test students' understanding, they are asked to write a lab report using similitude and their non-dimensional plot to predict the area of an 11''x 17'' sheet of paper. For this analysis, they are told not to simply multiply length by width, but to use their experimental plot from the 8.5" x 11" sheets. Moreover, they are asked to explain why this exercise is analogous to studying the forces of a scaled-down aircraft in a wind tunnel to predict the performance of the full-scale aircraft. It is expected that students will realize the 8.5" x 11" sheets they started with are geometrically similar to a 11''x 17'' sheet. However, there is no way to have run the experiment on the larger sheet of paper as it was not provided. By the same token, scale aircraft models predict performance before the larger aircraft they represent are built.

Finally students are asked to compare their prediction for the area of the 11''x 17'' sheet obtained through their experiment to the actual area determined by multiplying the paper's length by width.

Laboratory 06: Hydrostatic Stand Pipe

For liquid water, where 1) the density, ρ, does not change at reasonably shallow depths and 2) the gravitational coefficient, g, is fixed, the hydrostatic pressure at depth, $P(z)$, of the fluid can be expressed through the hydrostatic equation as

$$P(z) = P_o + \rho g z \tag{4}$$

where P_o is the ambient pressure above the water column, and z is the depth below the free surface.

As shown in Figure 2, the way this phenomenon is usually taught in brick-and-mortar fluids laboratories is by use of a hydrostatic standpipe; a several-meters-tall vertical polyvinyl chloride (PVC) pipe with ability to control the depth of water inside by draining to various known depths. The standpipe is connected to a shuttle manifold with embedded pressure gauges that is connected via flexible hose to the water in the pipe, creating a continuous water column. Moving the shuttle vertically along a ruler affixed to the stand pipe changes the depth of water above the pressure gauges on the shuttle relative to a fixed vertical scale. Thus, the water pressure as a function of depth can be determined experimentally.

Figure 2: (Left) A full-scale stand pipe is used in conventional fluids labs to demonstrate hydrostatic pressure at depth. (Right) For remote learners, a miniaturized stand pipe has been created with multiple pressure gauges attached to a traveling manifold.

Instead of a stand-pipe many meters tall, the *@HOLM*™ version of this laboratory uses a 2000 mL plastic graduated cylinder, about 40 cm tall, with a threaded hole drilled in the bottom. As shown in Figure 2, a flexible tube connected between this hole and a shuttle manifold with pressure gauges attached creates a continuous water column for hydrostatic pressure measurement. While the lab-scale stand pipe pressure gauges read in large-denomination PSI, the *@HOLM*™ version uses much more sensitive pressure gauges that read in ounces-per-square-inch, inches of water, and 0-3 PSI.

As shown in Figure 3, despite the small stature of the *@HOLM*™ experiment, enough water depth is available in the 2000 mL graduated cylinder for students to experimentally validate the linear nature of the hydrostatic equation. Need for gauge calibration (see Figure 3) might also become apparent during experiments, providing remote student learners an additional hands-on opportunity to open and calibrate the pressure gauges.

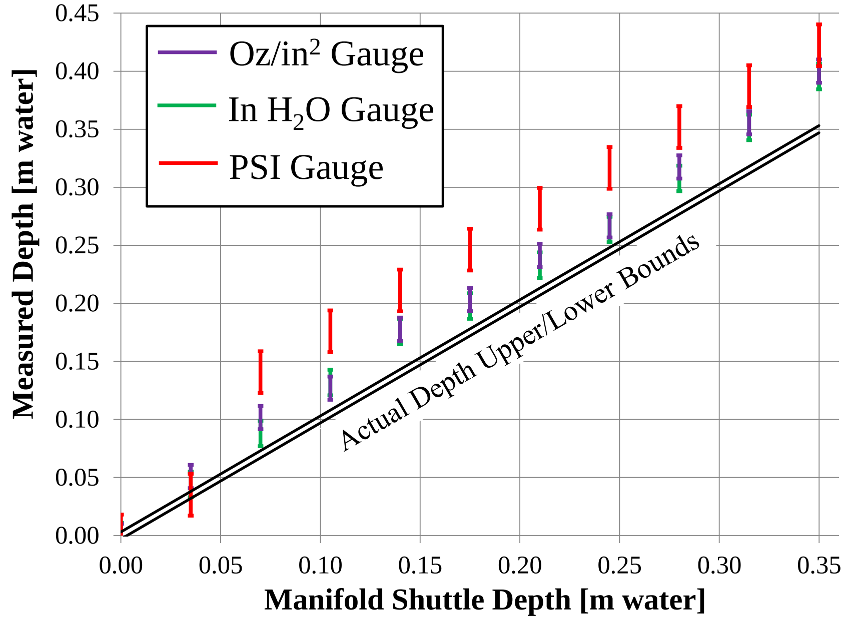

Figure 3: Depth measurement comparison of the actual fluid depth to readings from multiple pressure gauges (with uncertainty ranges) on the miniaturized *@HOLM*™ stand pipe indicates need for pre-experiment gauge calibration.

Laboratory 08: Momentum Conservation & Jet Force

The Reynolds Transport Theorem in the form of the Momentum Conservation Equation is demonstrated experimentally for the remote learner using a ducted computer fan atop a digital scale, pictured in Figure 4 and shown schematically in Figure 5. The Fan takes in ambient quiescent air radially, $\bar{v}_{r,in}$, at its downward-facing side and directs it upward through a metal duct at $\bar{v}_{z,out}$. The fluid velocity through the duct is controlled by varying the speed of the fan, which has an on-board pulse width modulation circuit. The velocity through the duct is directly interrogated using a pitot-static probe meant for drones connected to a Dywer mark ii 35 manometer. [23]

To measure force induced by changing the velocity of the air drawn into the fan, the entire apparatus sits upon an Ohaus ScoutPro digital scale. [24] The scale is zeroed before the fan is turned on so any resulting increase in measured force is due only to momentum change from the air imparting force onto the apparatus. The upward flowing air through the system induces a downward force on the apparatus, which is countered by an upward normal force between the scale and the fan, $\bar{f}_{z,scale-fan}$, to hold the apparatus is fixed position. By modulating and measuring duct velocity and then measuring the corresponding force induced on the scale, the momentum conservation equation, which reduces to the following form for this system, can be verified experimentally.

$$\bar{f}_{z,scale-fan} = \rho_{air} A_{duct} \left(\bar{v}_{z,out}\right)^2 \tag{5}$$

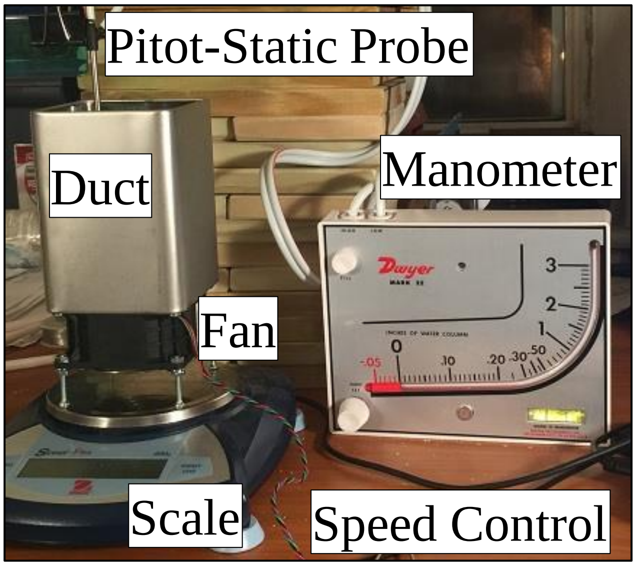

Figure 4: The desktop-scale momentum conservation measurement experiment for remote learners includes a variable-speed fan drawing air through a duct to induce a vertical force that is registered by a digital scale. Air velocity through the duct is measured by a pitot-static probe inserted into the flow, which is connected to a Dwyer Mark ii 35 manometer.

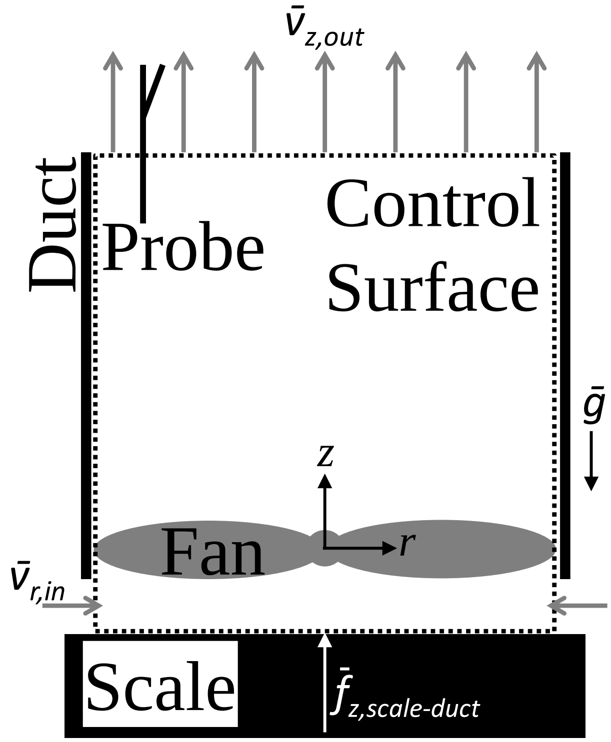

Figure 5: This schematic shows the operation, fluid flows, and forces upon the *@HOLM*™ linear momentum conservation apparatus. Air is drawn upward through the experiment, inducing a downward force, which is countered and measured by a digital balance. The fluid velocity, which can be varied by changing the fan speed, is measured by a pitot-static probe inserted into the flow.

To test the prototype's function, data were taken at two different fan speeds and the corresponding induced force on the scale recorded. For the first experiment, $\bar{v}_{z,out} = 0.225\text{"}\ H_2O = 9.56 \pm 0.11\ \frac{m}{s}$, corresponding to a scale mass of $m = 0.0385$ kg, and yielding a force of $\bar{f}_{z,scale-fan} = 0.378 \pm 0.05\ N$. Solving Eq. (5) for these conditions indicates induced force should be 0.718 ± 0.016 N.

For the second experiment, $\bar{v}_{z,out} = 0.17\text{"}\ H_2O = 8.31 \pm 0.12\ \frac{m}{s}$, corresponding to a scale mass of $m = 0.0300$ kg, and yielding a force of $\bar{f}_{z,scale-fan} = 0.294 \pm 0.05\ N$. Solving Eq. (5) indicates induced force should be 0.542 ± 0.016 N.

The mismatch in force between theory and experiment for the prototype occurs because the turbulent velocity profile at the nozzle outlet (where the pitot-static probe is measuring) is not fully developed. There is a flow "dead spot" at the center of the duct created by the fan motor housing. The resulting velocity profile is shown qualitatively in Figure 6. The uneven velocity profile can be observed with the manometer when the pitot-static probe is manually rastered across the duct opening. So, the theoretical result of Eq. (5) based on a single velocity measurement at the periphery of the duct where velocity is higher gives an over-prediction in force (exactly what is observed).

Work is ongoing to create a flow apparatus with shorter entrance length (see Laboratory 13: Measuring Velocity Profile and Development Length) where a fully-developed turbulent velocity profile is achieved upstream of the pitot-static probe. This next iteration on the experiment will be insensitive to velocity measurement location and should return consistent theory-experiment results.

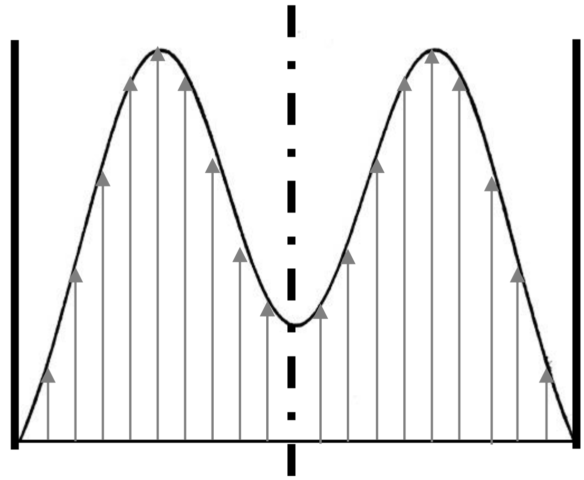

Figure 6: This qualitative representation of the momentum conservation experiment velocity profile shows the “dead spot” in the center created by the fan housing. An inadequate entry length is provided for the profile to become fully developed. Due to non-uniformity of the velocity profile, a single velocity measurement at the outlet input to Eq. (5) gives an erroneous result.

Laboratory 13: Measuring Velocity Profile and Development Length

Velocity profile in a circular duct and corresponding hydrodynamic entry length are demonstrated and measured experimentally using a PVC pipe with a variable speed drone fan drawing air into one end. As shown in Figure 7 (Right), students measure velocity at the pipe outlet using a pitot-static probe meant for drones attached to a Dywer Mark ii 35 manometer. The probe is fixed to an inexpensive digital caliper, which serves two functions. First, it rasters the probe across the diameter of the pipe, keeping it aligned with the pipe’s axis. Second, it records the probe’s location (accurate to better than 0.2 mm) with respect to the pipe wall. Since exit lengths for turbulent flow are nil and only meaningful for laminar flow with Reynolds numbers below 100, [25] there are no concerns that the presence of the probe or the mounting caliper will propagate upstream and disrupt the velocity profile.

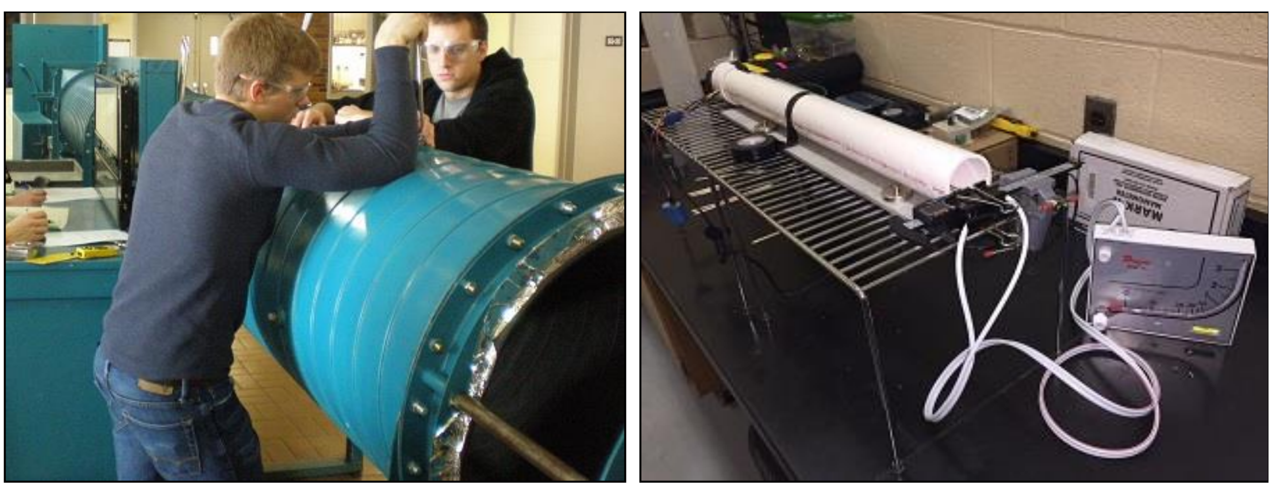

Figure 7: This laboratory-scale velocity profile interrogation experiment (Left) uses HVAC ducting with a diameter too large to allow the flow to develop fully within the length of the apparatus. By contrast, the smaller diameter of the *@HOLM*™ velocity profile interrogator (Right) enables a measureable fully developed turbulent velocity profile to be formed in less than 1 meter of pipe.

By using different fan speeds and pipe diameters, the apparatus is able to achieve a range of Reynolds numbers from as low as Re_D = 1700 (laminar flow) using 1/2" pipe and v_{ave} = 2 m/s to over Re_D = 100,000 (turbulent flow) using 2" pipe and v_{ave} = 30 m/s. A representative experimental turbulent velocity profile is shown in Figure 8. Since the Dywer Mark ii 35 manometer has readability down to only 0.01" water (~ 2.5 Pa, or about 2 m/s flow velocity), the remote student learner will use a differential pressure gauge with higher resolution and sensitivity to interrogate the velocity profile when the experiment is run in laminar flow mode. For laminar flow experiments, a Dwyer 2000-00N Magnehelic Differential Pressure Gage [26] is plumbed in parallel with the Dwyer manometer. With some care, the Magnehelic gage can resolve differential pressures to better than 0.0025" water (~0.62 Pa, or about 1 m/s flow velocity). To protect the Magnehelic gage from damage at higher flow velocities, it is isolated from the rest of the system by normally closed button valve, which the student must manually open when it is safe to do so to take measurements.

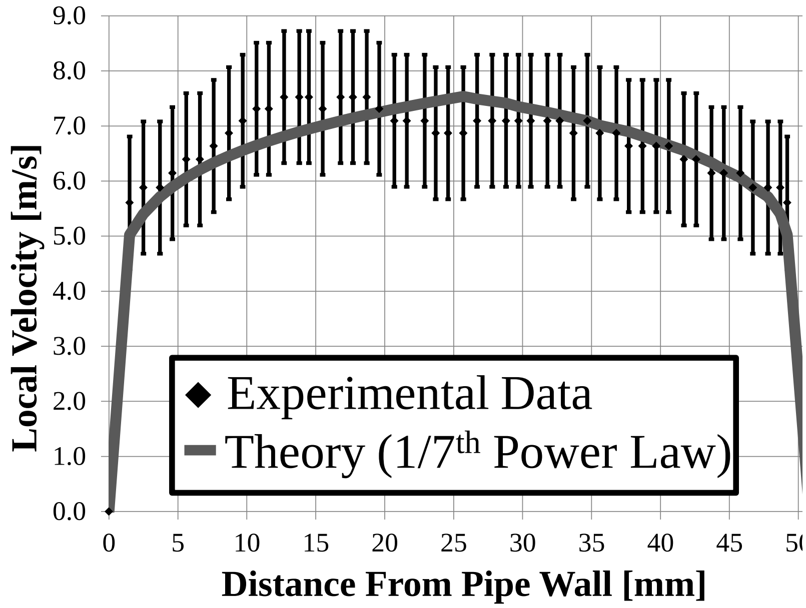

Figure 8: Correspondence between the theoretical 1/7th Power Law internal pipe flow turbulent velocity profile and the velocity profile experimentally measured by the *@HOLM*™ experiment show the two agree within experimental uncertainty.

Considering the empirical formulas for hydrodynamic entry length to achieve fully developed flow,

$$L_{e,laminar} = 0.5DRe_D \quad (6)$$

$$L_{e,turbulent} = 1.359D(Re_D)^{\frac{1}{4}} \quad (7)$$

Fully developed velocity profiles can be attained at reasonable pipe length for turbulent flows in the lower turbulent Reynolds number range. For a two-inch-diameter pipe with $v_{ave} \approx 7$ m/s ($Re_D \approx$ 24,000), the entry length is 0.86 meters (just under 3 feet of PVC pipe). As shown by real experimental data taken with this configuration using a 3-foot pipe length, the turbulent velocity profile is fully developed and agrees within experimental uncertainty to the shape of the theoretical fully developed turbulent velocity profile,

$$u(y) = u_{max}\left(\frac{y}{R}\right)^{\frac{1}{7}} \quad (8)$$

To visualize velocity profile development, three sections of PVC 0.3-meter-long are linked together to make a continuous pipe 0.9 meters long, which exceeds the $Re_D \approx 24{,}000$ turbulent flow entry length of 0.86 meters. The sections are connected using repair couplings, which allow the PVC sections to slide together leaving a smooth wall that does not upset the flow near the wall. As shown conceptually for laminar flow in Figure 9, the student experimenter first measures the velocity profile using the shortest PVC section; they should find an undeveloped profile. The experimenter then adds the second section, making a medium length pipe. The profile is measured again, and it should appear more developed. Finally, the experimenter adds the last pipe section, creating a pipe exceeding the flow development entrance length. Upon measuring the velocity profile of the longest iteration, the experimenter should see fully developed flow. After collecting data at three pipe lengths, the experimenter should be able to reconstruct a velocity profile development chart similar to Figure 9 (C).

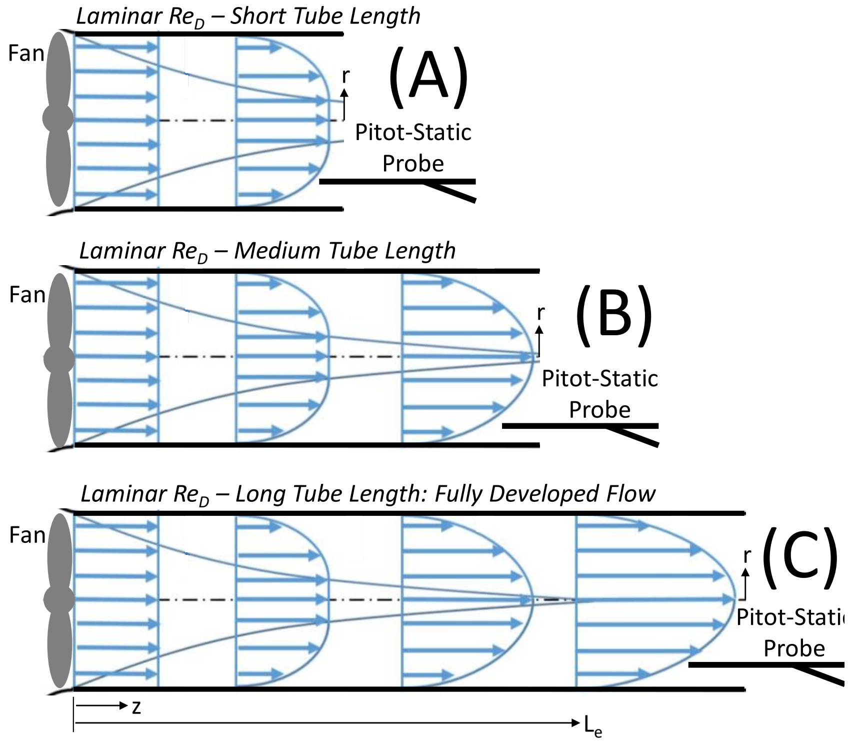

Figure 9: The development of a pipe flow velocity profile is experimentally measured using air pushed by a fan through pipes of increasing lengths.

Laboratory 18: Conservation Laws and the Radial Hydraulic Jump

Hydraulic jumps are used in fluid mechanical applications as varied as controlling the flow of rivers to reduce shoreline erosion to flood-cooling workpieces during metal milling. A simple radial hydraulic jump (Figure 10, for example) is formed when a vertical fluid jet impinges on a flat surface and spreads radially. Upstream of the jump, the Froude number exceeds 1 because the fluid velocity is greater than the surface wave propagation speed; this regime is called supercritical flow. As the fluid spreads to greater radii, continuity causes the flow velocity to drop, and eventually the Froude number becomes less than one – subcritical flow. Supercritical flow is analogous to supersonic flow in that surface waves cannot propagate upstream information about disturbances in the flow. In this flow regime, objects placed in the flow throw off surface shock waves. Subcritical flow is analogous to subsonic flow. The point of transition between supercritical and subcritical flow where Froude number is 1 is the hydraulic jump where the liquid instantly changes from a thin fast sheet to a thicker laminar structure.

Depending on the needs of the Fluid Mechanics course, hydraulic jumps can be used as analogies to shock waves in transonic flow and to demonstrate the concept of shock waves. Alternatively they can be used to illustrate a system where mass and momentum conservation are applied simultaneously from Reynolds Transport theorem to produce a viable model for this interesting flow phenomenon. As shown in Figure 11, the Reynolds transport theorem can be applied to a control volume that encompasses a radial hydraulic jump

$$\frac{DB}{Dt} = \int_{CV} \frac{\partial}{\partial t}(\rho b)dV + \int_{CS} \rho b(\boldsymbol{V}.\boldsymbol{n})dA \tag{9}$$

For mass conservation, B and b are m and 1 respectively. For linear momentum conservation, B and b are mV and V, respectively. The symbols m and V represent mass and velocity. In the equation D/Dt, t, ρ, V, A, and $\boldsymbol{n}$ denote material derivative, time, density, volume, area, and unit normal vector, respectively.

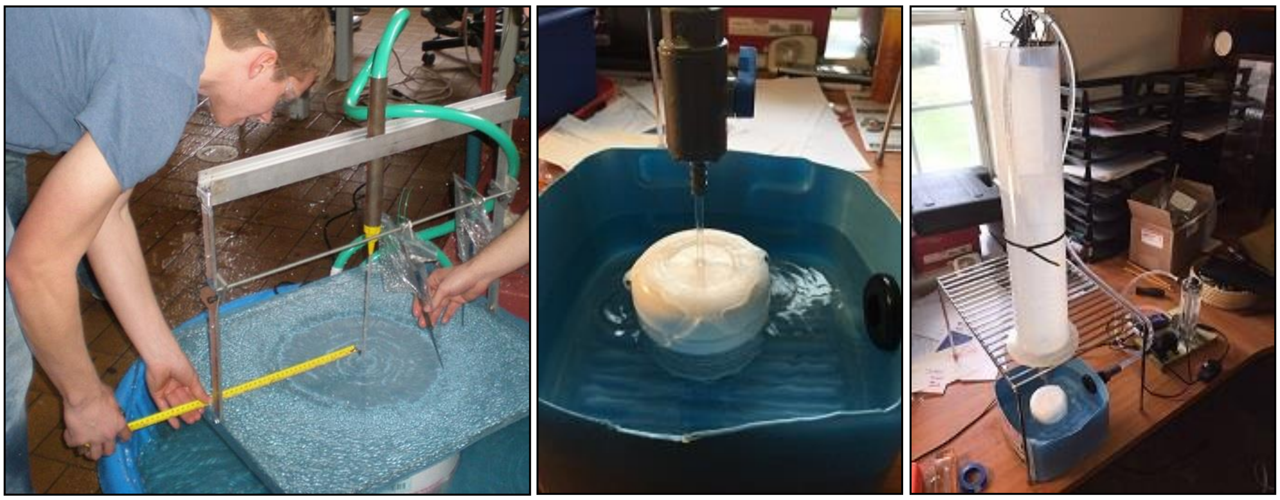

Figure 10: Students using a laboratory-scale circular hydraulic jump apparatus (Left) measure key jump parameters like radius and jump height. This concept is miniaturized via an *@HOLM*™ experiment that produces a small, stable circular hydraulic jump (Center) whose physical features can also be measured. The miniaturized system (Right) is small enough to fit on the desktop of a remote learner and be boxed and shipped to their location.

Application of mass conservation on the radial hydraulic jump control volume of Figure 11 gives the following relation:

$$V_1 r_1 h_1 = V_2 r_2 h_2 \tag{10}$$

Neglecting the friction force at the fluid's bottom, linear momentum conservation applied to the hydraulic jump control volume of Figure 12 gives the following expression (where g is the gravitational acceleration):

$$\frac{g}{2}(r_1 h_1^2 - r_2 h_2^2) = r_2 h_2 V_2^2 - r_1 h_1 V_1^2 \tag{11}$$

From observation, it is known that $h_1 \ll h_2$, therefore, Eq. (11) can be simplified to

$$\frac{g h_2^2}{2} \approx h_1 V_1^2 \tag{12}$$

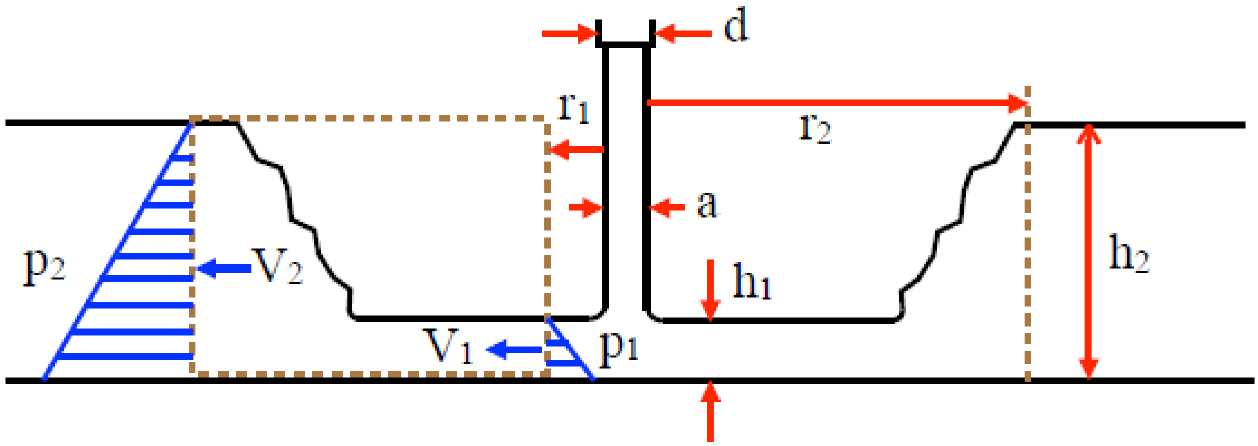

Figure 12: Key geometric parameters in cross section for a simultaneous mass and momentum conservation analysis of a control volume that includes the circular hydraulic jump.

Following some assumptions and algebraic manipulation covered during the supporting online lecture, the following expression emerges.

$$R = \frac{4\dot{Q}^2}{g(\pi h d)^2} \tag{13}$$

Equation13, which is an expression for the jump's radius, R, is validated experimentally using the *@HOLM*™ hydraulic jump apparatus shown in the Center and Right frames of Figure 11. The student experimenter uses calipers to measure R and the nozzle diameter, d; fluid volume flow rate from the nozzle, $\dot{Q}$, is measured by rotameter; and fluid height after the jump, h_2 is found via a color-changing dip stick placed in the water.

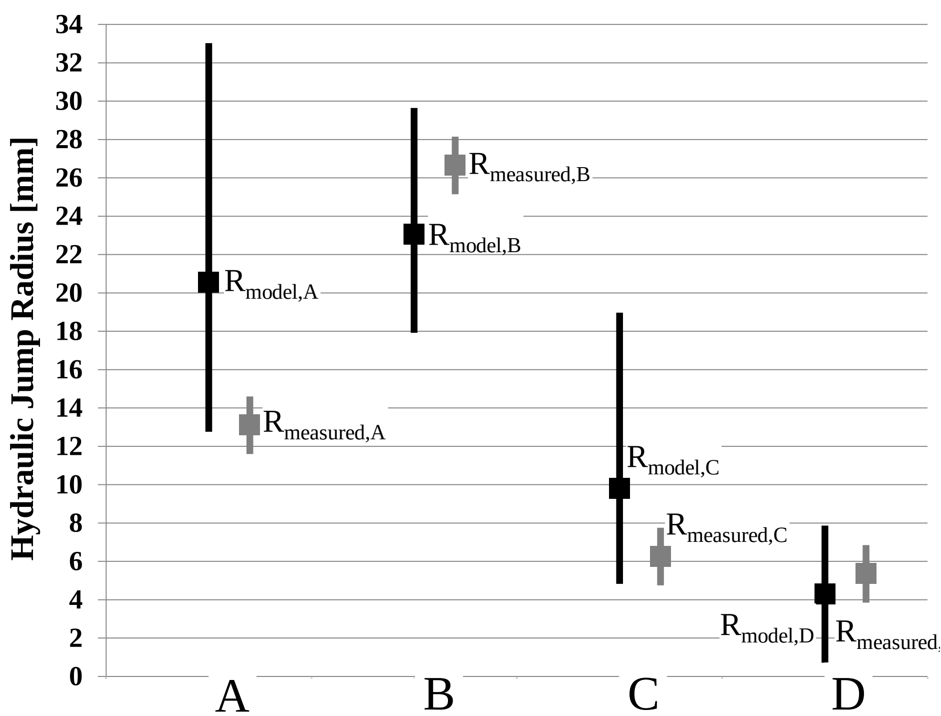

Figure 13: Four independent experiments with different volume flow rates were conducted on the *@HOLM*™ hydraulic jump apparatus. In all four cases, the theoretical hydraulic jump radius for the conditions set matched the measured jump radius within experimental uncertainty, validating that the experiment functions as expected.

Figure 13 shows validation results of four experiments using the *@HOLM*™ hydraulic jump apparatus at four different fluid volume flow settings. Jump radius is measured directly (the reported $R_{measured}$ values in Figure 13), and then it is calculated theoretically (the reported R_{model} values in Figure 13) from measurements of other experimental parameters combined into Eq. (13). Figure 13 shows that for each of these four different experiments, $R_{measured}$ agreed with R_{model} within experimental uncertainty, validating the performance of the hydraulic jump apparatus.

Assessment

When laboratory kits are sent to remote learners, no instructor will be physically present to troubleshoot them. Minor issues can be answered via telepresence. However, the experiments must generally be reliable and repeatable, and their assembly and operation must be intuitive for students using them remotely.

To evaluate the viability and robustness of *@HOLM*™ experiments in the hands of students, select laboratories are being beta-tested at Tennessee State University (Figure 14). Labs are spirally inserted into an existing lecture-based Fluid Mechanics course taught in-person. Students receive extra credit for completing the lab experiment. We report here on results from the Hydraulic Jump Experiment (Laboratory 18 described above), which was the first one beta tested.

Before coming to the lab, students were asked to view an hour-long lecture posted online, which reviews relevant content taught in the lecture and demonstrates correct use of the experiment. A similar video will be provided to remote learners for each lab experiment shipped as part of the course. Following pedagogical best practice, videos are limited to 8-9 minutes each to avoid short-cycle attention span lapses documented to occur in longer STEM lectures. [27] So, seven 9-minute videos combine to make a complete lecture, allowing students to frequently take breaks if needed. The videos are organized into a YouTube playlist to play in succession so students can choose to watch as little or as much as they like in one sitting. The hydraulic jump lecture videos are posted at the following URL's:

Video 1: https://youtu.be/vvrfBTT8C2Y
Video 2: https://youtu.be/J5c9X2ZzlDs
Video 3: https://youtu.be/stC663arWR8
Video 4: https://youtu.be/9_EfwhqJmoc
Video 5: https://youtu.be/3C5SnIcqVUc
Video 6: https://youtu.be/eUtPUaIjFHs
Video 7: https://youtu.be/iuMsw7yZvAM

Once in the lab, students work on the experiment in pairs as there are currently only two apparatuses available to serve a large class. Pairing students doubles participant throughput. An instructor is present to observe and answer student questions if they arise. However, the instructor may not touch or point to the apparatus and can only verbally answer questions. This restriction is meant to replicate the level of student-teacher interaction that will be possible via telepresence.

Student users are observed by the instructor as they complete the experiment. The instructor also notes opportunities for experimental apparatus usability improvement based on overserved student interactions with the apparatus. Once the values needed to solve Eq. (13) and generate the data shown in Figure 13 are collected, the students report their results to the instructor.

Indirect Assessment
Once the students' interaction with the experiment is finished, each student participant completes an anonymous indirect assessment survey to quantify 1) their self-reported understanding of what transpired in the lab, 2) their level of enthusiasm for the hands-on activity they completed, and 3) their attitude toward adding additional experiments to their course, which is currently entirely lecture-based.

The assessment contains the following nine Lickert-Like Scale Indirect Questions (LLSIQ's), which are scored using the following scale: 1) Strongly Disagree, 2) Disagree, 3) Neutral, 4) Agree, and 5) Strongly Agree.

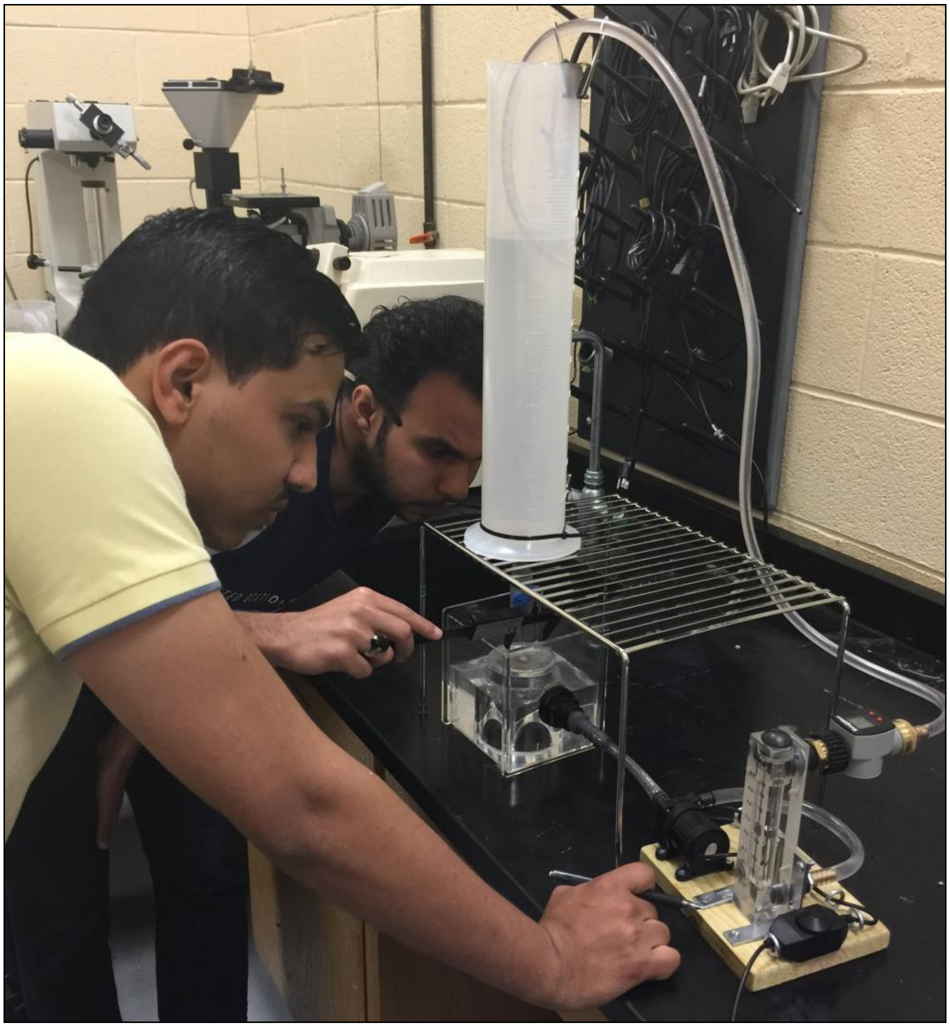

Figure 14: To provide assessment and usability data, Tennessee State University upper-division mechanical engineering undergraduates beta-tested the @*HOLM*™ hydraulic jump experiment for extra credit in a lecture-based Fluid Mechanics class taught in-person.

LLSIQ1. This laboratory exercise corresponds well to concepts I learned in class.
LLSIQ2. This laboratory improved my understanding of course concepts.
LLSIQ3. This laboratory provided practical hands-on experience in fluid mechanics.
LLSIQ4. I feel I can explain the mechanics and theory of this laboratory to a peer.
LLSIQ5. The laboratory instructions were clear and easy to follow.
LLSIQ6. The laboratory experiment could be completed without instructor support or intervention.
LLSIQ7. I enjoyed performing this experiment.
LLSIQ8. It would be beneficial to complete similar experiments supporting other class concepts.
LLSIQ9. I recommend that laboratory exercises be incorporated into more lecture courses.

Averaged student LLSIQ survey results for the hydraulic jump experiment are tabulated in Figure 15 with data aggregated from N = 14 student respondents. On average, the surveyed student cohort

"Agreed" or "Strongly Agreed" with all nine survey statements, indicating a highly beneficial and enjoyable educational experience that could generally be completed without faculty intervention.

The survey also included three Open-Ended Indirect Questions (OEIQ's) to mine students' experience for more lab improvement opportunities. The questions and representative responses are outlined here.

OEIQ1. What did you like about this laboratory experience?

A: I liked the setup of the lab. It was easy to perform.

A: The lab helped me a lot to understand the concept of hydraulic jumps.

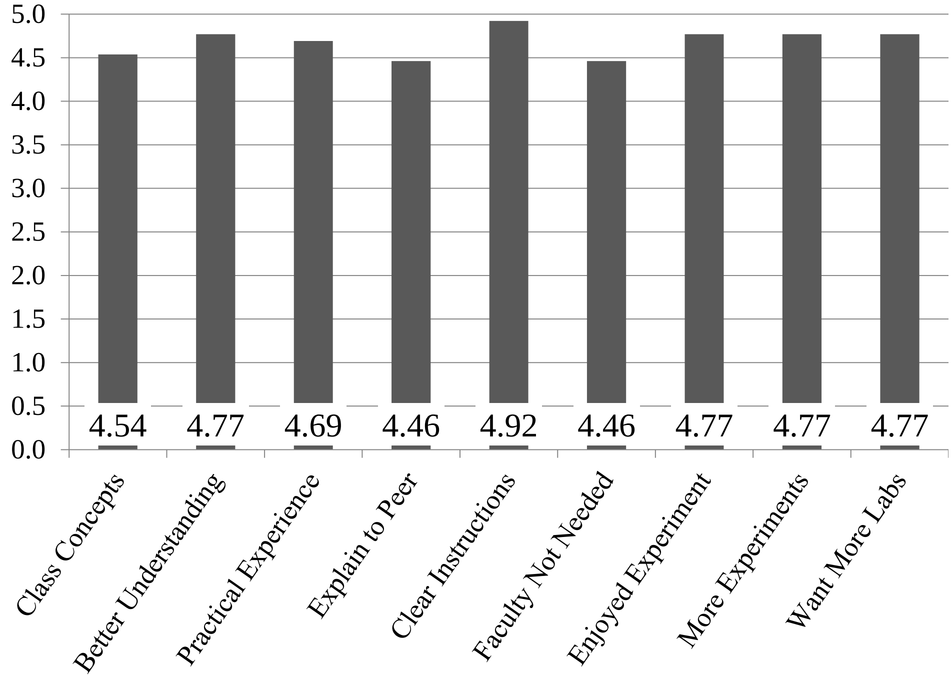

Figure 15: Fourteen (N = 14) student beta-testers of the *@HOLM*™ radial hydraulic jump experiment responded to the indirect survey. The results indicate that students "Agree" or "Strongly Agree" on average with all survey statements. These results suggest student participants felt the experiment was both beneficial and enjoyable.

A: The experiment was broken down step-by-step in the online lecture, and the videos were really easy to follow. I liked having the flexibility to take breaks as needed between short segments.

OEIQ2. What did you dislike or find difficult about this laboratory experience?
OEIQ3. What would you change or improve about this laboratory experience?

In addressing both these questions, students made various comments about the usability of the experiment including comments on the sensitivity of the pump control; inability to reach the caliper jaws all the way into the jump to measure diameter; and the aspiration of air bubbles into the pump at higher flow settings, which confounded volume flow rate measurement. Students also suggested dying the water with food coloring to improve its visibility. All student suggestions for usability improvements as well as observations from the instructor on how students interacted with the experiment will be addressed in the next iteration of the hydraulic jump experiment.

<u>*Direct Assessment*</u>
As student participants left the laboratory, they were given a homework assignment directly related to the lab. The assignment, which is provided in the Appendix, includes a single question broken

into four parts. It asks students to quantitatively evaluate representative data given for the hydraulic jump experiment and calculate parameters like fluid height, flow velocity, and Froude number before and after a radial hydraulic jump. Students are given one weekend to work the problem. It was thought better to evaluate students using a uniform data set for assessment rather than allow each student to use their own experimental data. This approach makes comparison of student results easier than evaluating their individual solution approaches with numerous disparate experimentally-generated data sets.

As an incentive to invest time in solving the direct assessment homework problem correctly, students received additional Fluid Mechanics course extra credit proportional to the grade they earned on the assignment. Collected assignments are graded by the instructor. In addition to numerical grades, the instructor also evaluated how well each student's script demonstrated achievement of technical Direct Assessment Learning Outcomes (DALO's), which are independent of the students' grades.

The assessment contains the following five DALO's, which were scored by the instructor using the following Likert-like scale: 1) Strongly Disagree, 2) Disagree, 3) Neutral, 4) Agree, and 5) Strongly Agree.

DALO1. Demonstrate proper units conversion.
DALO2. Recognize correspondence between equation and the physical experiment set-up.
DALO3. Apply mass conservation to solve for unknown quantities.
DALO4. Use the Froude Number expression to evaluate fluid structure.
DALO5. Recognize how Froude Number corresponds to subcritical and supercritical flow conditions.

Data were collected from N = 10 student participants who carried out the hydraulic jump lab experiment and submitted the associated quantitative homework assignment. The results of their averaged DALO achievement are tabulated in Figure 16. In summary, these students demonstrated high achievement of the first four DALO's with neutral to adequate achievement recognizing how Froude number corresponds to subcritical and supercritical flow conditions. Importantly, this topic is not typically covered in mechanical engineering fluids courses. So, students had no prior exposure to it in the face-to-face lectures. Only the online lecture associated with this lab experiment covered subcritical/supercritical flow structures and the conditions differentiating them. So, it is possible that students' relative weakness in achieving DALO #5 arose from lack of exposure to the underlying concept in their face-to-face lectures.

Discussion

In at least three ways, *@HOLM*™ labs show promise to provide student learning experiences superior to conventional brick-and-mortar labs. First, learners build, test, and troubleshoot *@HOLM*™ labs themselves, providing valuable experience in constructing and operating engineering systems. Conventional lab experiments are prebuilt and set up by a technician or instructor, denying students the opportunity to learn from building. Second, each learner has their own *@HOLM*™ lab setup, allowing them to complete each experimental step themselves; progress at their own self-directed pace; and deeply explore serendipitous, fortuitous, or interesting derivative phenomena along the way without interfering with the learning of others. Third, each learner is responsible for completing every lab experience independently, ensuring their learning experience is rich and comprehensive.

By contrast, brick-and-mortar laboratory hardware is costly (both in capital and floor space). Thus, universities do not usually have one experimental apparatus for each student; meaning students almost always complete conventional labs in teams (Figure 7 [LEFT], for example). Teams tend to be monopolized by one or two dominant students who complete the experiments while others observe. Passive watchers miss critical hands-on learning opportunities and forfeit deep understanding. The historical benefit of laboratory group work is that students can seek help from within their group as they process data to produce lab reports. However, in the online Fluid Mechanics course that accompanies *@HOLM*™ labs, that benefit is preserved through peer interactions during live learning moments and on community discussion boards. Students stuck on any laboratory construction, process, or analysis step can also arrange with the instructor a one-on-one video chat where the instructor can see the student's set-up via Webcam and talk him/her through halting aspects.

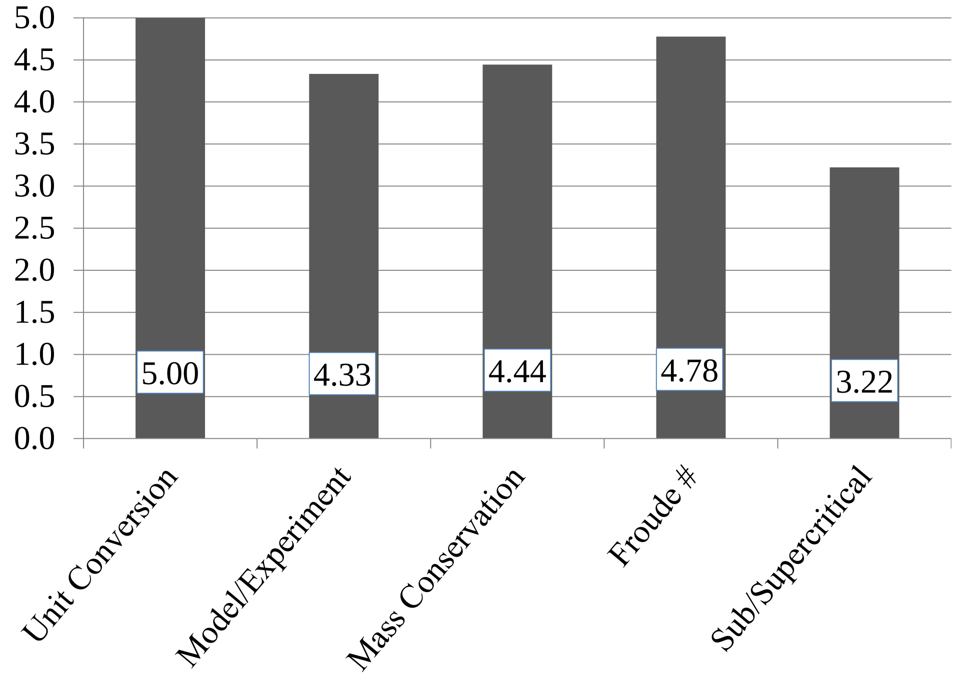

Figure 16: Ten (N = 10) student beta-testers of the *@HOLM*™ radial hydraulic jump experiment submitted the homework assignment associated with the lab. From student scripts, Achievement of direct learning outcomes was evaluated by the instructor. On average, students scored well in all outcomes assessed except recognition of how Froude Number corresponds to subcritical and supercritical flow.

In the Fluid Mechanics course with *@HOLM*™ laboratories, students build and run their own experiments, collect and analyze their own data, and independently author their own quantitative laboratory reports to summarize their findings. Each of these processes allows learners to discover, navigate, and produce knowledge. Lab exercises are integrated into relevant course sections so the knowledge being explored through labs is complementary and timely with other aspects of the course. By contrast, many mechanical engineering curricula have laboratory components running asynchronously with lecture components, creating a disconnect in time between learned theory and the supporting hands-on lab experience. We believe that by beginning to offer laboratory-based mechanical engineering undergraduate courses online, remote learners will benefit from all the powerful learning advantages online education already affords students in many other disciplines.

Conclusions

We report the creation of *@HOLM*™ fluid mechanics laboratory kits paired with an undergraduate mechanical engineering fluids course taught exclusively online. This fully online lecture/lab course combination can be seamlessly inserted into any ABET-accredited baccalaureate mechanical engineering curriculum. The physical lab kit, which can contain up to 18 unique experiments, is small and inexpensive, enabling it to be shipped to a remote learner. The student then assembles each experiment, collects data, and performs analysis at their remote location.

Here, we described 5 *@HOLM*™ experiments among the 18 available in the fluid mechanics kit: 1) Non-Dimensionalisation and Similitude, 2) Hydrostatic Stand Pipe, 3) Momentum Conservation and Jet Force, 4) Measuring Velocity Profile and Development Length, and 5) Conservation Laws and the Radial Hydraulic Jump. Explanations of the underlying fluids phenomenon evoked by each experiment are provided, showing how they work. Quantitative results are also provided comparing the experimental output of each laboratory to theoretical predictions to show that they produce measurable and meaningful results, which can form the basis for engineering analysis by remote student learners. The kit experiments retain the features, robustness, and rigor of full-scale brick-and-mortar laboratories now in use at all ABET-accredited undergraduate mechanical engineering programs.

Results from both indirect and direct assessment of student learning outcome attainment are summarized for one representative experiment, the radial hydraulic jump laboratory. This experiment was beta-tested by upper-division mechanical engineering undergraduates enrolled in a conventional lecture-based fluid mechanics course taught in-person. After viewing supplemental lecture content online and completing the experiment, students filled out surveys (indirect assessment) and completed an instructor-evaluated homework assignment (direct assessment). Results from both assessments indicate that students demonstrated meaningful learning from this lab, they enjoyed the experience, and they could complete the experimental activities without instructor intervention.

We believe this first successful demonstration of hands-on experimental mechanical engineering laboratory kits, which can be sent to remote learners taking courses on-line, represents a critical new advance in the way undergraduate mechanical engineering curricula are delivered to students. Using *@HOLM*™ experiments, lab-intensive undergraduate mechanical engineering courses in ABET-accredited programs can now be taught online for the first time. Fully online mechanical engineering B.S. programs akin to the ABET-accredited electrical engineering B.S. programs at Stony Brook University and Arizona State University will surely follow.

Acknowledgements

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Researcher Incubator Hypothesis, [28,29] a corollary pedagogy within the Narrative of *New Learning*. [30] TURN student Muteb Alkhamisi contributed to analysis underpinning the @*HOLM*™ Non-Dimensionalisation and Similitude laboratory.

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Appendix: Student Direct Assessment Homework Problem

A hydraulic jump generator has been built (Figure 1) that will create a steady-state circular hydraulic jump in water. A dimensionless parameter called the Froude number, Fr, determines whether the fluid is supercritical or subcritical:

$$Fr = \frac{v}{\sqrt{hg}}$$

where v is the local fluid velocity, h is the depth of the fluid, and g is gravitational acceleration.

In supercritical fluid, which is observed upstream of the jump, the fluid velocity exceeds the speed at which information propagates as waves across the fluid surface; this phenomenon is similar to supersonic fluid flow. In subcritical fluid, which is observed downstream from the jump, the fluid velocity is less than the surface wave information propagation speed.

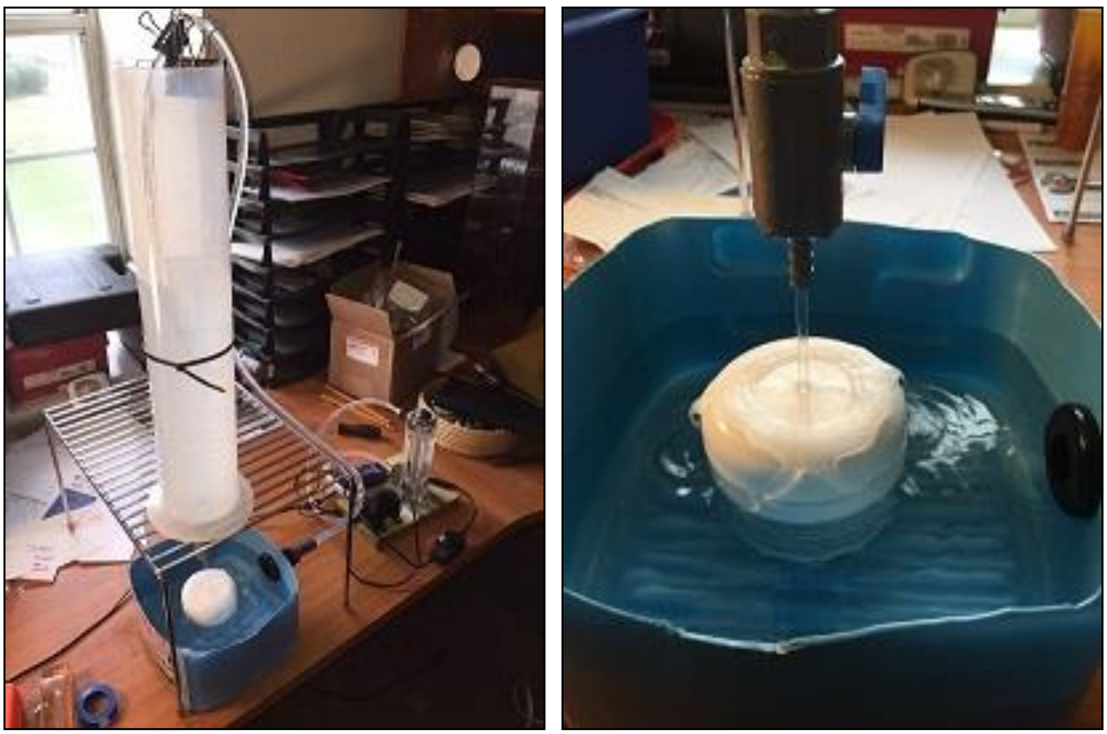

Figure 1: The hydraulic jump generator (left) produces a steady circular hydraulic jump in water (right) that can be experimentally measured and analyzed.

With water flowing at 0.7 liters/minute from a nozzle 3.75 mm in diameter, the observed diameter of the hydraulic jump is 3.8 cm.

1. What is the fluid height after the jump?

2. What is the fluid height before the jump?

3. Is the fluid subcritical or supercritical at a radius of 0.5 cm from the jump? What is the Froude number at this location?

4. Is the fluid subcritical or supercritical at a radius of 2.0 cm from the jump? What is the Froude number at this location?