JOURNAL OF ONLINE ENGINEERING EDUCATION, VOL. 10, NO. 1, ARTICLE 3

A Miniaturized Circular Hydraulic Jump for Remote On-Line Fluid Mechanics Instruction

M.J. Traum[1] and F. Hadi[2]
[1] Engineer Inc., Gainesville, FL, USA
[2] Tennessee State University, Nashville, TN, USA

***Abstract*—Toward the goal of a fully online mechanical engineering bachelor degree program with curriculum-integrated hands-on laboratory experiments, a miniaturized circular hydraulic jump teaching lab kit was created and tested. This small and inexpensive kit is intended for shipment to remote learners who then assemble the experiment, collect data, perform analysis, collaborate with online peers, and author lab reports from their homes. While tiny and economical, the experiment retains the features, robustness, measurability, and rigor of its full-scale counterparts. The experiment's aim is to predict circular hydraulic jump diameter given measured working fluid volume flow rate, nozzle diameter, and fluid height after the jump. This predication is then validated by measuring the hydraulic jump diameter directly. Within experimental uncertainty, theorical and experimental results agree over a range of user-set volume flow rates into the jump. Junior and Senior mechanical engineering students enrolled in a conventional Fluid Mechanics course tested the experiment in an environment simulating remote learning conditions. Their learning outcome achievement was measured through both indirect and direct assessments. Learning outcomes were achieved to a very high level, demonstrating that this remote learning laboratory approach is a viable alternative to conventional brick-and-mortar mechanical engineering teaching labs.**

***Index Terms*—Distance Engineering Education, Hands-On Learning Module (@HOLM™), Hydraulic Jump, Online Engineering Laboratory.**

I. INTRODUCTION

Despite availability of technologies enabling distance engineering Master's programs [1] and ABET-accredited undergraduate electrical engineering programs offered online, ABET-accredited undergraduate mechanical engineering programs taught exclusively on-line do not yet exist [2]. While the University of North Dakota claims an online ABET-accredited, B.S. mechanical engineering degree, students still "need to come to campus to complete portions of the program," including hands-on laboratory work [3].

While engineering educators express difficulty offering hands-on laboratory experiences that satisfy ABET objectives as a major barrier [4], there is no fundamental accreditation or practical restriction preventing undergraduate mechanical engineering degrees from being offered entirely online. In fact, the feasibility of such programs has already been explored [5]. Nonetheless, entrenched sentiment in the mechanical engineering education community favors need for laboratory experiments in brick-and-mortar college facilities.

We propose an alternative with potential to revolutionize distance undergraduate mechanical engineering education: Hands-On Learning Module (@HOLM™) laboratory kits. These kits maintain the pragmatic laboratory experiences central to mechanical engineering curricula while allowing undergraduate engineering courses to be taught to remote learners fully on-line [6]. Learners receive in the mail an inexpensive @HOLM™ kit containing experiments integrated into the online engineering course they are taking. Following assembly instructions, learners build each apparatus, run experiments, collect and analyze data, collaborate and share results with online peers, and author lab reports.

We report development and user testing of a circular hydraulic jump educational lab experiment following the @HOLM™ approach that maintains the features, robustness, and rigor of its full-scale counterparts. While small and economical, the apparatus produces observable and consistent fluidic phenomena previously only evoked and measurable via full-scale brick-and-mortar teaching lab equipment.

II. PEDAGOGICAL BACKGROUND

Blosser summarized the history of laboratories 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" [7]. In the intervening period, numerous reviews and studies confirmed that laboratories are a critical component of student learning in the sciences and engineering [8, 9, 10].

In their historical description of undergraduate engineering education laboratories, Feisel and Rosa point out that by the 1990's, ABET had established criteria explicitly requiring laboratory practice. Lack of feasible ways to offer remote lab experiences prior to the Internet made brick-and-mortar laboratory teaching facilities essential [11]. Later, the ABET EC2000 criteria struck explicit laboratory instruction requirements, but their language still included references to experiments, use of modern tools, and institutional support [12]. Implied need instilled a sense that brick-and-mortar teaching labs were mandatory to retain ABET accreditation. Although ABET's newest accreditation standard removed explicit or implied need for laboratories, many engineering programs institutionalized attainment of ABET Criterion 3 Student Outcomes (1) and (6) through brick-and-mortar laboratories [13]:

(1) an ability to identify, formulate, and solve complex engineering problems by applying principles of engineering, science, and mathematics;

(6) an ability to develop and conduct appropriate experimentation, analyze and interpret data, and use engineering judgment to draw conclusions.

Years of reliance on brick-and-mortar laboratories to satisfy ABET outcomes instilled in the engineering education community an erroneous belief that laboratory experiences must occur in brick-and-mortar facilities. Moving away from these established practices against institutional inertia is formidable, but some successful remote engineering laboratory experiences have been reported.

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 the importance of design skills while 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.

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 student group studied loading and deflection of a real 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 deflecting cantilever computer simulation with no corresponding physical hardware [15]. These researchers found that the remote and computer simulated labs were at least as effective as the traditional brick-and-mortar experience. In some cases, students responded positively to the remote lab experiences and performed better on follow-on assessments. In a more detailed follow-up study using the same three cantilever experiment delivery methods, Corter and colleagues studied 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. Despite their perceptions, students who completed remotely operated labs fared better on tests [16].

In a private communication, L. D. 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 [17]. Professsor Feisel indicated this work had been absorbed into the online B.S. electrical engineering program at Stony Brook University. Indeed, Stony Brook University as well as Arizona State University both achieved ABET accreditation for fully online electrical engineering B.S. degree programs in 2014, proving that brick-and-mortar facilities are not essential to obtain program accreditation through ABET's Engineering Accreditation Commission (EAC). Numerous pedagogical researchers report successful implementation of electrical engineering labs, modules, courses, and full electrical engineering programs at the undergraduate level [18, 19, 20].

Stony Brook offers the final two years of its four-year electrical engineering 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 [21]. 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 [22, 23].

III. TECHNICAL BACKGROUND

Beyond our own work [6], we are aware of no published reports in the engineering education literature that develop and deliver hands-on fluid mechanics laboratories to remote learners in undergraduate mechanical engineering programs. Fluids lends itself to building a portfolio of hands-on experiments for remote mechanical engineering learners because 1) relevant experiments can be safely implemented at home and 2) ready supply of the primary needed ingredient – liquid water – is available at home. Using a small electric pump to circulate water, dynamic fluid phenomena both long-lasting and stable enough for quantitative measurement can be created. Moreover, extreme forces are not needed (as in tensile testers for material mechanics courses), nor are extreme temperatures needed (as in boilers for thermodynamics or heat transfer courses). Thus, many fluids experiments are very safe to operate without direct instructor supervision.

We elected to develop an experiment for hydraulic jump measurement because 1) the phenomenon is easy to set up; 2) multiple introductory theoretical fluid dynamics concepts are illustrated [e.g., our apparatus can describe Froude Number with subcritical / supercritical flow as well as Reynolds Transport Theorem]; 3) hydraulic jumps are well-understood and well-described in the literature; and 4) jumps possess enough complexity that a simple experiment can be expanded to demonstrate more advanced fluid topics in the future, such as surface tension effects and flow instability.

Liu and Lienhard experimentally showed the thinness of liquid films normally encountered in circular hydraulic jumps favor surface tension as dominant in establishing the shape of the circular jump for impinging jets [24]. As surface tension effects decrease, a series of instabilities occur at the jump surface that eventually leads to turbulent flow and air entrainment similar to that seen in classical planar open-channel jumps. However, before the jump becomes unstable, the surface tension stabilization creates a vortex on the front surface of the jump in addition to a wall vortex in the subcritical region along the wall near the jump. According to these researchers, standard control volume momentum balance cannot fully describe circular hydraulic jumps. Inclusion of a downstream / upstream depth ratio and jump surface stability parameters theory are required for a complete description. While we recognize this complexity, we will show that momentum balance alone achieves theoretical results consistent enough with the experimental for high-quality undergraduate instruction.

Our derivations use techniques from Brechet and Ne´da who obtained experimental scaling laws for jump radius as a function of 1) flow rate, 2) drop height and 3) viscosity, in good agreement with earlier results in the literature [25]. The theoretical results they obtained using the ideal fluid approximation, however, are only in partial agreement with experiments. They, nonetheless, improved their theoretical work by considering real, viscous liquids leading to the same scaling law for jump radius in the three approaches they used. These results are confirmed by their work experimentally as well as by more refined approximations.

Experiments of Bush et al. [26] revealed that in addition to steady polygonal jumps, a new hierarchy of steady asymmetric jump structures with instability wavelengths depending on the surface tension, fluid density and speed of the radial outflow at the jump exist. These structures resemble many unexpected shapes: cat's eyes, three- and four-leaf clovers, bowties, and butterflies. While not used for experiments reported in this paper, this hydraulic jump instability attribute could be used in future @HOLM™ labs to dramatically show flow instability. These researchers also explained the symmetry-breaking instability by proposing a physical picture in which the jump is viewed as the inner portion of a torus and by considering the Rayleigh–Plateau pinch-off of the initially circular jump. They also made a key observation that that the axial symmetry-breaking instabilities only occur for jumps with backflows at the front surface of the jump confirming the work of Ellegaard et al [27].

Kasimov [28] developed a theory of steady circular hydraulic jumps using the depth-averaged Navier–Stokes equations. This theory provides a base-state solution for the analysis of the jump instability. The theory, satisfactorily, also describes the details of the downstream flow such as the downstream depth. This is crucial because the flow downstream of the jump determines the state behind the jump and therefore determines the jump radius. In the derivation we present, fluid height downstream of the jump is an important parameter that students must measure to estimate jump diameter. Kasimov also showed that the steady-state circular jump does not exist if the surface tension exceeds a certain critical value. A gas dynamic analogue of the circular hydraulic jump – a detonation wave is discussed, which could be useful in the future for development of @HOLM™ experiments that teach compressible flow to distance learners without need to develop or store high pressures.

Passandideh-Fard et al. [29] numerically simulated a circular hydraulic jump by solving mass and momentum conservation equations together, using the volume-of-fluid method, to track the free surface advection. Their numerical simulation accurately predicts the jump's location and behavior. They also studied the effects of different parameters including volumetric flow rate, downstream height, viscosity, and gravity on the jump radius and its characteristics using water and ethylene glycol. Parts of this analysis are also used in our derivation.

IV. APPARATUS DESCRIPTION

Several examples in the engineering education literature report mechanical engineering instructors using low-cost experimental systems or common household items for laboratories in fluid mechanics [30] and thermal-fluid-sciences [31, 32]. With respect to economy, @HOLM™ labs are similar. However, instructors who developed these inexpensive experiments did not teach distance learning or online courses, and none of the experiments were designed to be mailed to remote learners.

Hydraulic jumps are used in applications as varied as controlling river flow for shoreline erosion reduction to flood-cooling workpieces during metal milling. A simple circular hydraulic jump (Figure 1, for example) is formed when a vertical fluid jet impinges on a flat horizonal surface. 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.

Figure 1. A representative circular hydraulic jump formed when a vertical water jet impinges on a flat horizontal surface.

Supercritical flow is analogous to supersonic flow in that surface waves cannot propagate information upstream about disturbances in the downstream 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.

The complete apparatus is shown in Figure 2. Users set the fluid flow rate of an aquarium pump using a Pulse Width Modulation (PWM) controller (Figure 3). Water exits the pump through an analog rotometer for volume flow rate measurement, and it is deposited in a reservoir made from a 2000 mL graduated cylinder. Flow leaves the reservoir through a valve-nozzle combination embedded in the bottom of the graduated cylinder. Users adjust the fluid flow rate into the hydraulic jump by changing the setting on the nozzle valve. The aquarium pump flow rate is then user-adjusted with the PWM controller to keep the fluid level in the graduated cylinder fixed.

Vertical jet flow leaves the nozzle and impinges on a flat, circular acrylic surface where the hydraulic jump is formed. Fluid then spills radially outward over the edge of the acrylic surface into an acrylic catchment where it pools in preparation to be returned to the pump.

Needed parameters measured for the experiment include the volume flow rate (determined by rotometer), the nozzle diameter, and jump diameter; the latter two are measured using calipers. Also needed is the fluid height after the jump, which is measured by coating a plastic straw with water-soluble paint. The straw is dipped in the water beyond the jump radius, and the flow strips off the paint to reveal fluid depth.

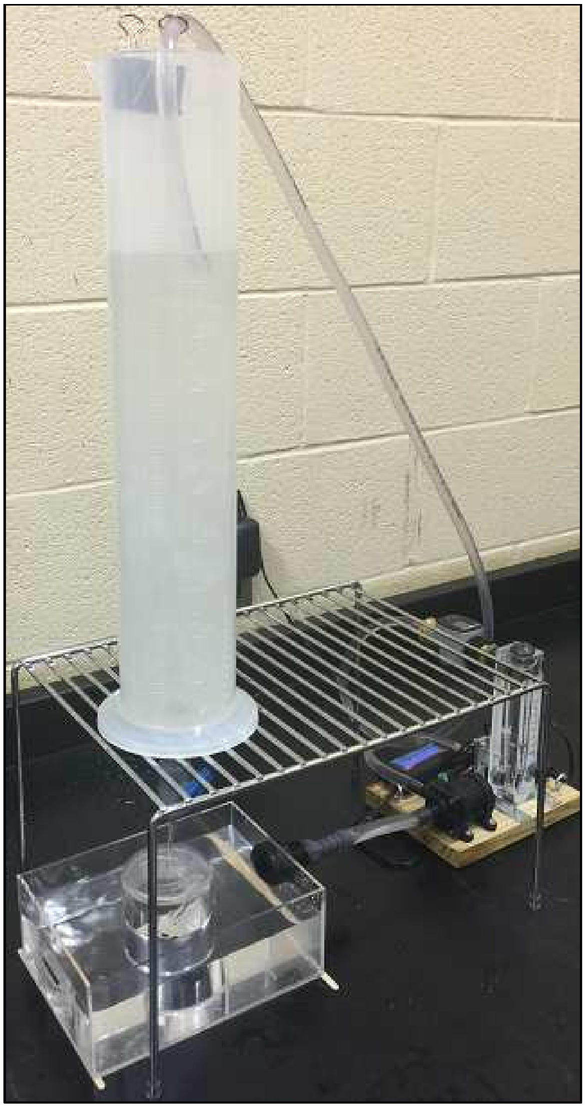

Figure 2. The complete hydraulic jump @HOLM™ experimental apparatus.

V. THEORY DERIVATION & VALIDATION

The jump radius, R, is determined via Reynolds Transport Theorem applied to an annular control volume in Figure 4 containing fluid with inner radius upstream and outer radius downstream of the jump. The radius is found as a function of volumetric flow rate ($\dot{Q}$), nozzle diameter (d), and fluid height after the jump (h_2). The general Reynolds Transport Theorem form is

$$\frac{DB}{Dt} = \int_{CV} \frac{\partial}{\partial t}(\rho b)dV + \int_{CS} \rho b(\boldsymbol{V}.\boldsymbol{n})dA \qquad (1)$$

where B and b are m and 1 for mass conservation and mV and V for momentum conservation, respectively. The symbols m and V represent mass and velocity. In Eq. (1), D/Dt, t, ρ, V, A, and n denote material derivative, time, density, volume, area and unit normal vector, respectively.

Application of mass conservation on the control volume of Figure 4 results in the following relation

Figure 3. The hydraulic jump pump and flow rate component includes an aquarium pump, which moves fluid through the experiment and is speed-controlled by Pulse Width Modulation (PWM).

$$V_1 r_1 h_1 = V_2 r_2 h_2 \qquad (2)$$

Application of momentum conservation yields

$$\frac{Dm\boldsymbol{V}}{Dt} = \int_{CV} \frac{\partial}{\partial t}(\rho \boldsymbol{V})dV + \int_{CS} \rho \boldsymbol{V}(\boldsymbol{V}.\boldsymbol{n})dA \qquad (3)$$

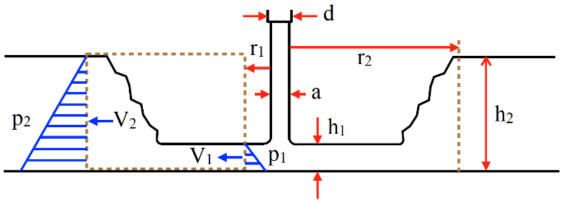

Figure 4. Schematic representation of a circular hydraulic jump indicating variables used in the theoretical analysis.

Considering a steady state hydraulic jump, Eq. (3) can be simplified to

$$m\frac{D\boldsymbol{V}}{Dt} = m\boldsymbol{a} = \Sigma \boldsymbol{F} = \int_{CS} \rho \boldsymbol{V}(\boldsymbol{V}.\boldsymbol{n})dA \qquad (4)$$

where a and F denote acceleration and force, respectively. Neglecting the friction force at the fluid's bottom (assuming small viscosity), the only forces remaining on the control volume arise from pressure gradients in the fluid; Thus,

$$\int_0^{h_1} 2\pi r_1 \rho g z dz - \int_0^{h_2} 2\pi r_2 \rho g z dz = -2\pi r_1 h_1 \rho V_1^2 + 2\pi r_2 h_2 \rho V_2^2 \qquad (5)$$

where g and z are the acceleration of gravity and the vertical component of the coordinate system, respectively. Simplifying Eq. (5) gives

$$\frac{g}{2}(r_1h_1^2 - r_2h_2^2) = r_2h_2V_2^2 - r_1h_1V_1^2 \qquad (6)$$

Substituting Eq. (2) in Eq. (6) gives

$$\frac{g}{2}(r_1h_1^2 - r_2h_2^2) = r_1h_1V_1^2(\frac{r_1h_1}{r_2h_2} - 1) \qquad (7)$$

At the jump $r_1 \approx r_2 = R$. Therefore,

$$\frac{g}{2}(h_1^2 - h_2^2) = h_1V_1^2(\frac{h_1}{h_2} - 1) \qquad (8)$$

From observation, $h_1 \ll h_2$; therefore, Eq. (8) can be simplified to

$$\frac{gh_2^2}{2} \approx h_1V_1^2 \qquad (9)$$

Next, consider the jet coming out of the nozzle in Figure 5

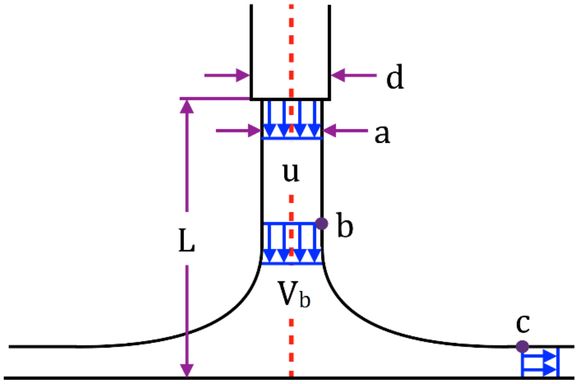

Figure 5. Schematic of a vertical jet impinging on a flat horizontal surface including variables used in continuity analysis.

By considering the acceleration of the liquid in the jet as g and using the continuity equation inside the vertical jet, for a jet falling under gravity, we obtain [25]

$$a = (\frac{\pi^2 gL}{8\dot{Q}^2} + \frac{1}{d^4})^{-\frac{1}{4}} \qquad (10)$$

where L and a are height of the jet and jet diameter, respectively. Mass continuity between the falling jet column and the fluid after impingement gives

$$\dot{Q} = \frac{\pi}{4}a^2u = 2\pi r_1h_1V_1 \qquad (11)$$

where u is the jet velocity. For the streamline connecting point b to point c in Figure 5, the Bernoulli equation gives

$$p_b + \frac{1}{2}\rho V_b^2 + \rho g z_b = p_c + \frac{1}{2}\rho V_c^2 + \rho g z_c \qquad (12)$$

On the surface of the liquid, $p_b = p_c = p_{atm}$ and for b arbitrarily close to c, $z_b \approx z_c$ because gravitational impact is small. Therefore,

$$V_b = V_c \qquad (13)$$

Since the fluid is assumed inviscid, the internal fluid profile of both the jet and the flow after impingement is flat. Thus $u = V_b = V_c = V_1$. Therefore

$$\dot{Q} = \frac{\pi}{4}a^2V_1 \qquad (14)$$

Combining Eqs. (11) and (14) and noting that at the jump $r_1 = R$ gives

$$h_1 = \frac{a^2}{8R} \qquad (15)$$

Inserting Eqs. (14) and (15) in Eq. (9) gives

$$R = \frac{4\dot{Q}^2(\frac{\pi^2 gL}{8\dot{Q}^2} + \frac{1}{d^4})^{\frac{1}{2}}}{g(\pi h_2)^2} \qquad (16)$$

This result is compatible with the literature [25]. For high $\dot{Q}$ and small L, $a \approx d$. Using this simplification, Eq. (16) can be simplified to

$$R = \frac{4\dot{Q}^2}{g(\pi h_2 d)^2} \qquad (17)$$

Equation 17 is the theoretical benchmark equation for a circular hydraulic jump introduced in the online lectures supporting this experiment. It contains all the parameters measured by students as described the previous section, and it facilitates comparison of experiment to theory. Students measure the hydraulic jump radius, R, directly by placing caliper jaws across the jump diameter. They also measure $\dot{Q}$, h_2, and d as described above. Plugging these three measured parameters into the right side of Eq. 17 gives a theoretical value for R, which is compared to the R experimentally measured. Figure 6 shows comparisons for directly measured hydraulic jump radius ($R_{measured}$) versus the theoretical value radius (R_{model}) obtained from Eq. 17 given known Q, h_2, and d parameters occurring within four runs of the experiment with different user-set volume flow rates into the jump.

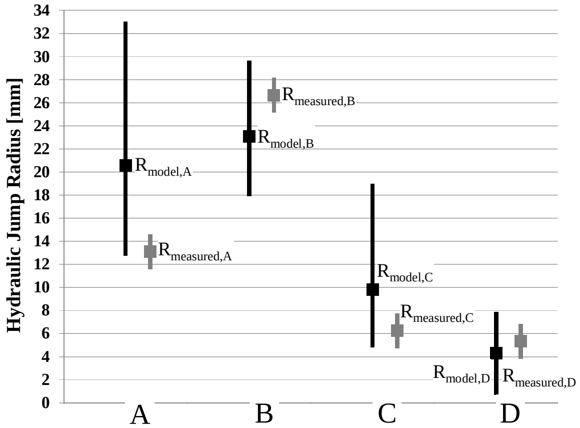

Figure 6. Experimental hydraulic jump radius measurement results from four representative runs showing agreement between theory and experiment.

As shown in Figure 6, despite selection of four different volume flow rates for study, the experiment consistently returned $R_{measured} \approx R_{model}$ within the range of expected experimental uncertainties. This theory / experiment agreeemnt builds confidence in the experiment to yield consistent results consistent with theory.

VI. PEDAGOGICAL ASSESSMENT

When laboratory kits are sent to and used by remote learners taking mechanical engineering courses online, 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 the @HOLM™ hydraulic jump experiment in the hands of students, this lab kit was beta-tested at Tennessee State University (TSU) with undergraduate students (Figure 7). Hydraulic jump online lecture content and the supporting lab experiment were inserted into an existing TSU lecture-based fluid mechanics course taught in-person. While participation in this module was voluntary, students received extra credit for completing the lab experiment to motivate their involvement.

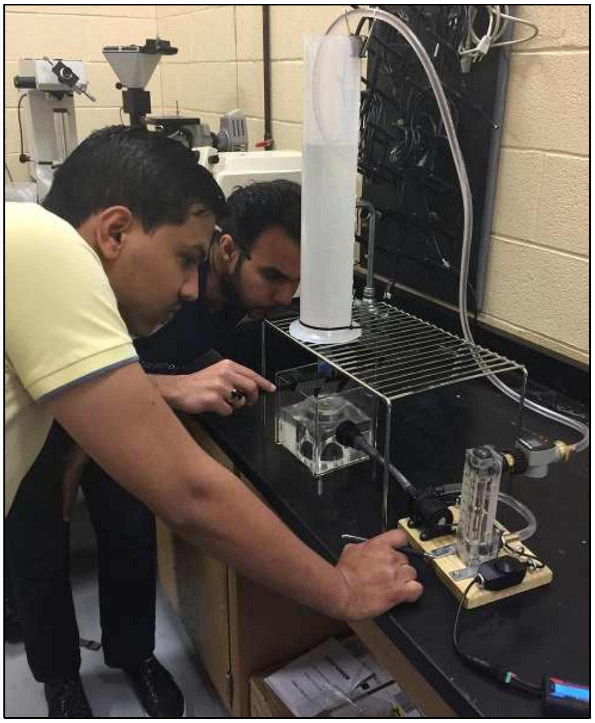

Figure 7. Students running the hydraulic jump experiment.

Before attending the lab, students were asked to view an hour-long seven-part lecture posted online, which reviewed relevant content taught in the face-to-face lecture and demonstrated correct use of the hydraulic jump experiment. Following pedagogical best practice, videos were limited to 8-9 minutes each to avoid short-cycle attention span lapses documented to occur in longer STEM lectures [33]. Seven 9-minute videos combined to make a complete lecture, allowing students to frequently take breaks if needed. The videos were organized into a YouTube playlist to play in succession so students could choose to watch as little or as much as they liked in one sitting.

Once in the lab, students worked with the experiment in pairs as there were only two apparatuses available to serve a large class. An instructor was present to observe and answer student questions if they arose. However, the instructor was limited to actions only available to a teacher remotely present via video chat. He did not touch or point to the apparatus, and he could only verbally answer questions. This restriction was meant to replicate the level of student-teacher interaction that will be possible via telepresence.

Students working in pairs with little or no instructor assistance 1) measured the nozzle diameter, 2) established a steady hydraulic jump by adjusting the value nozzle and aquarium pump speed, 3) determined fluid volume flow rate from the rotometer, and 4) measured the fluid height downstream of the jump. Once the values needed to solve Eq. (17) and generate the data shown in Figure 6 were collected, the students reported results to their instructor. They then competed a project assessment survey and were given a relevant take-home assignment.

A. Indirect Assessment

Once students' interaction with the experiment was complete, each participant filled out 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 contained nine questions tabulated in Table I to which student could respond on a Likert scale scored using the following scale: 1) Strongly Disagree, 2) Disagree, 3) Neutral, 4) Agree, and 5) Strongly Agree.

TABLE I.
INDIRECT ASSESSMENT SURVEY QUESTIONS

#	**Indirect Assessment Metrics**
1	This laboratory exercise corresponds well to concepts I learned in class.
2	This laboratory improved my understanding of course concepts.
3	This laboratory provided practical hands-on experience in fluid mechanics.
4	I feel I can explain the mechanics and theory of this laboratory to a peer.
5	The laboratory instructions were clear and easy to follow.
6	The laboratory experiment could be completed without instructor support or intervention.
7	I enjoyed performing this experiment.
8	It would be beneficial to complete similar experiments supporting other class concepts.
9	I recommend that laboratory exercises be incorporated into more lecture courses.

B. Open Ended Questions

The student exit survey also included three open-ended questions to mine students' experience for more lab improvement opportunities. The questions and representative responses are outlined in Table II.

TABLE II.
OPEN-ENDED SURVEY QUESTIONS WITH STUDENT RESPONSES

Q1: What did you like about this laboratory experience?
"I liked the setup of the lab. It was easy to perform."

“Seemed transparent and easy to follow.”
“It helped me a lot to understand the concept of hydraulic jumps and the purpose of creating one.”
“I learned how to do the lab without an instructor.”
“Fun, easy, safe, time saving. Overall it was amazing for students and enjoyable.”
“Organized well, easy to do, understandable. Not too long.”
Q2: What did you dislike or find difficult about this laboratory experience?
“The Pulse Width Modulation pump controller is a sensitive device to set it up, but it works.”
“Getting some of the dimensions was kind of difficult.”
“I found it difficult to get the volume flow rate stable.”
Q3: What would you change or improve about this laboratory experience?
“I would like to work with other students to improve the reading and make the scales more precise.”
“Measuring the diameter of the jump accurately was difficult. There is need to reduce the height of the container or have easier access for students to get better water depth readings.”
“I would like to see the same laboratory performed to produce different hydraulic jump shapes just out of curiosity.”
“A better pump arrangement is needed to avoid air getting into the pump.”
“Plus, I would make the water easier to see. Maybe add coloring to it.”

Student users gave helpful feedback about the usability of the experiment including comments on the sensitivity of the pump control; difficulty to reach the caliper jaws all the way into the jump to measure its 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 are being addressed in the next iteration of the hydraulic jump experiment as it is being updated from beta testing to deployment for online learners.

C. *Direct Assessment*

Student participants were given a graded homework assignment directly related to the lab. The assignment, which appears in a previous publication [6] 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 upstream and downstream of the circular hydraulic jump. Students were given one weekend to work the problem.

As an incentive to invest time in solving the direct assessment homework problem correctly, students received additional course extra credit proportional to the grade they earned on the assignment. Collected assignments were graded by the instructor. In addition to numerical grades, the instructor also evaluated how well each student’s script demonstrated achievement of Direct Assessment Learning Outcomes (Table III), which are independent of the students’ grades. The assessment contained the following five direct assessment learning outcomes, which were scored by the instructor using the following Likert scale: 1) Strongly Disagree, 2) Disagree, 3) Neutral, 4) Agree, and 5) Strongly Agree.

TABLE III.
LEARNING OUTCOMES EVALUATED BY DIRECT ASSESSMENT

#	Direct Assessment Metrics
1	Demonstrate proper unit conversion.
2	Recognize correspondence between equation and the physical experiment set-up.
3	Apply mass conservation to solve for unknown quantities.
4	Use the Froude Number expression to evaluate fluid structure.
5	Recognize how Froude Number corresponds to subcritical and supercritical flow conditions.

VII. RESULTS

To evaluate the utility of the hydraulic jump @HOLM™ lab kit and its ability to enable student achievement of learning outcomes, both indirect and direct data were evaluated.

A. *Indirect Assessment*

Averaged student indirect assessment survey results for the hydraulic jump experiment are tabulated in Figure 8 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.

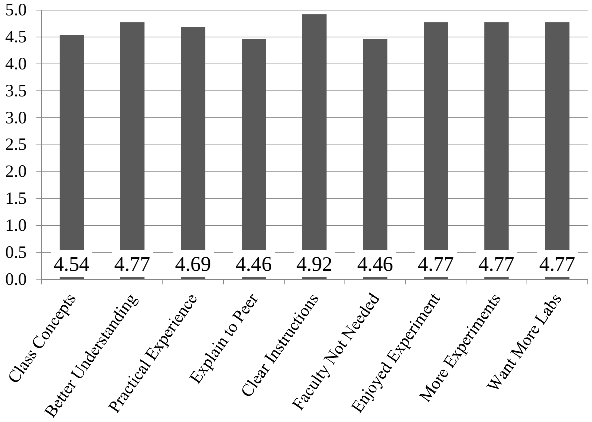

Figure 8. Indirect assessment results from student exit surveys.

B. *Direct Assessment*

Averaged results from students’ direct assessment learning outcomes achievement are tabulated in Figure 9. Data were collected from n = 10 student participants who carried out the hydraulic jump lab experiment and submitted the associated quantitative homework assignment. These students demonstrated high achievement of the first four learning outcomes with neutral to adequate achievement of the fifth: recognizing how Froude number corresponds to subcritical and supercritical flow conditions. Importantly, this topic was not covered in the face-to-face portion of the fluids course participating students were taking. So, they had no prior exposure to it in the course. Only the online lecture associated with the hydraulic jump lab experiment covered subcritical / supercritical flows and the conditions differentiating them. So, it is possible students’ relative weakness in the fifth outcome arose from lack of exposure to the underlying concepts in face-to-face lectures.

VIII. DISCUSSION

Certainly, the hydraulic jump @HOLM™ beta test described here did not perfectly replicate the experience future online learners will have conducting fluids experiments remotely from an instructor. The experiment was inserted into a face-to-face course, students worked in pairs, and the exercise was conducted in a brick-and-mortar lab environment. Nonetheless, the test provided valuable validation that transitioning a mechanical engineering fluids lab experiment from brick-and-mortar to a remote experience is feasible.

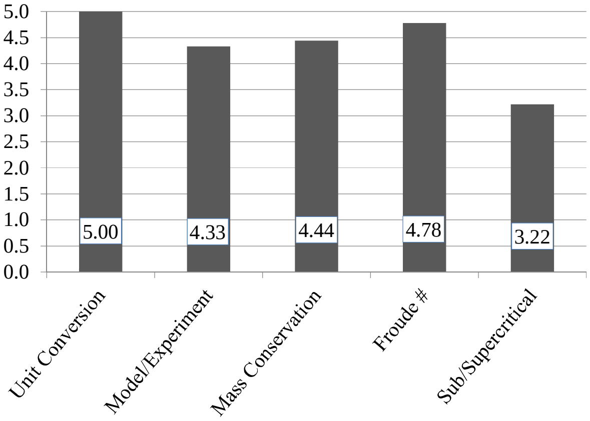

Figure 9. Direct assessment results from relevant homework problems.

Three critical findings arise from instructor observations and indirect / direct data collection. First, students are capable of successfully conducing the experiment without direct faculty intervention using only online video lectures for guidance. Second, indirect assessment data show students felt that they learned from the @HOLM™ lab experience. Third, direct assessment data show students did, in fact, learn from the experience.

A. Beneits of Student Experience with @HOLM™ Labs

Instructor observations of students working with the @HOLM™ hydraulic jump lab kit revealed at least three ways this approach provided student learning experiences equal to or superior than conventional brick-and-mortar labs. First, since learners individually build, test, and troubleshoot @HOLM™ labs themselves they gain valuable experience constructing and operating engineering systems. By contrast, conventional brick-and-mortar lab experiments are usually prebuilt and set up by a technician or instructor, denying students the opportunity to learn from building.

Second, when deployed to individual remote learners @HOLM™ labs give each student their own setup to explore in an environment with low peer influence. This learner-focused arrangement empowers students 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 or feeling peer pressure to move ahead with incomplete understanding.

Third, each learner is responsible for completing every lab exercise independently, ensuring their learning experience is rich and comprehensive. Universities usually do not provide one experimental apparatus for each student; students must almost always complete conventional labs in teams. Teams can be monopolized by one or two dominant students who complete the experiments while others observe [34]. Passive observers miss critical hands-on learning opportunities and forfeit deep understanding. 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 on their own.

A possible weakness of the @HOLM™ lab approach is that students cannot seek real-time help from peers as they process and contemplate to produce lab reports. However, in an online fluid mechanics course that accompanies @HOLM™ labs, rich peer interactions can occur during live learning moments and on community discussion boards. Students stuck on any laboratory construction, process, or analysis step can also arrange a one-on-one video chat with the instructor where that faculty member can see the student's set-up via Webcam and talk through challenging aspects.

B. Indirect Survey Results discussion

Extremely positive average student survey responses to the @HOLM™ hydraulic jump lab experiment was surprising. Certainly, this result captures the enthusiasm of students who felt they gained substantial learning from the lab experience. However, the unexpectedly positive student response might also result from the nature of the class, the way credit was conferred, and/or the state of TSU's existing fluids lab experiments.

The fluids class in which this experiment was run was planned as a purely lecture-based course with no lab component. So, positive indirect assessment responses might have resulted from the absence of other labs in the course – students were excited to see a real-world application of the theory they learned in lecture. If this supposition is true, any lab experiment, even a brick-and-mortar one, would have elicited the same positive student survey response. Along the same lines, student participation in the @HOLM™ experiment was optional. Not every fluids student chose to complete the hydraulic jump experiment. High-performing students excited about fluids (the ones who would naturally provide favorable survey responses) might have self-selected disproportionality to participate. Moreover, participation conferred extra credit (not regular credit) in the fluids course. So, students may have felt overly positive about the experience because it represented an easy way to boost their course grade. Finally, TSU's brick-and-mortar teaching facilities in the Energy-Thermal-Fluids area are aging. All students enrolled in this fluids class had previously taken TSU's Energy-Thermal-Fluids lab course and used teaching lab equipment that appeared used, old, and dilapidated compared against the brand new @HOLM™ hydraulic jump experiment. Maybe they were just excited to be working with new equipment on a novel experiment, and that sentiment colored positively their survey responses.

C. Direct Assessment Results Discussion

Student capabilities directly assessed through a quantitative take home assignment were also surprisingly high for four of the five skills evaluated. As with indirect assessments, a possible explanation is that high-performing student participations self-selected to do the @HOLM™ lab exercise. So, the measured high skills demonstration may reflect the predisposition of high-performing students choosing to participate while others did not.

Also interesting is lower average student performance on skills related to evaluating subcritical / supercritical flow. As stated above, students did not receive any face-to-face instruction on this topic in the face-to-face portion of the class. The online videos students watched in preparation for the @HOLM™ lab did contain this content. Direct assessment weakness in this one area may illuminate a weakness in online asynchronous versus face-to-face synchronous instruction. On the other hand, suspiciously low performance on this isolated topic might reflect the fact that students saw all other tested topics twice and subcritical / supercritical flow only once. Hence, higher scores on other topics may simply reflect more student familiarity in those areas.

Ultimately, high average student performance on most directly assessed skills illustrates that remote teaching experiments conducted in isolation from direct instructor assistance can teach mechanical engineering fluids to students. In other words, this result supports the supposition that @HOLM™ labs could replace face-to-face brick-and-mortar lab experiences, enabling institutions to offer lab-intensive mechanical engineering courses online to remote learners while providing students needed exposure to content and practice with skills that meet desired outcomes.

D. Institutional Beneits @HOLM™ Labs

From the perspective of educational institutions, @HOLM™ experiments provide at least three additional benefits beyond positive student experience and ability to attain learning outcomes through an alternate lab delivery technique. First, brick-and-mortar laboratory hardware is usually expensive in up-front capital expenditure, maintenance costs, and physical floor space. By contrast @HOLM™ labs are inexpensive, modular, and tiny. It is therefore expected that annual costs to run a lab class with @HOLM™ kits will be less than the conventional brick-and-mortar alternative. In addition, because the kits are small enough to ship, they are also small enough to easily store. One possible permutation enabled by availability of @HOLM™ kits is the option to simultaneously run face-to-face and distance engineering education courses where students receive the same content and enjoy the same lab experiences online as they do in-person. For students taking the lab in a brick-and-mortar environment, different @HOLM™ kits can be brought out each week for student use. They can then be easily disassembled and stored without taking up a permanent footprint in the teaching lab, freeing up space for additional experiments or other modular uses.

The second institutional benefit @HOLM™ kits provides is the option and flexibility to offer online courses with lab components to attract tuition-paying remote learners not able to enroll in conventional programs due to geographic or time constraints. In parallel, the option to offer online sections benefits faculty by opening a wealth of new effective teaching opportunities enabled by Internet instruction, particularly the ability to deliver content to students asynchronously and on-demand.

Third is elimination of need to upgrade existing equipment piecemeal. After making large capital investments in conventional lab equipment, institutions often find it desirable to perform upgrades one part at a time to keep experiments current or stay within budget constraints. For example, to keep up with changing technologies or industry standards, schools sometimes improve legacy capital teaching equipment by updating computer interfaces, swapping in individual sensors, or switching out single obsolete/damaged components while preserving most of the original hardware. Over time, teaching equipment resembles Frankenstein's monster and contains several different generations of components that often were not designed to work together. Not only does the equipment look unprofessional, degrading student (and ABET auditor) impressions of teaching facilities, but faculty often then have to manage second-order issues arising from incompatible components that degrade the student learning experience. The @HOLM™ lab kits are inexpensive enough that units can be replaced when the time comes with newer models where the entire system is updated to the latest components and technology and integrated into a device whose components and software are designed to work together.

IX. CONCLUSIONS

We report a successful test and assessment of the @HOLM™ lab kit approach to mechanical engineering laboratory instruction using undergraduate students enrolled in a fluid mechanics course. Although this test took place as part of a face-to-face course and the exercise was conducted in a brick-and-mortar teaching lab environment, the equipment and conditions were set to mimic the student experience of online remote learners. To our knowledge, this example represents the first time delivery viability of a hands-on fluid mechanics experiment for remote leaners has been reported and assessed in the peer reviewed literature. A circular hydraulic jump @HOLM™ lab kit experiment was used by students to study both Froude Number and the Reynolds Transport Theorem phenomena typically be taught in an undergraduate mechanical engineering fluid mechanics course. The kits are miniaturized versions of a full-scale brick-and-mortar teaching laboratory experiment made small enough to be packaged and shipped to a remote learner taking a fully online mechanical engineering class online via the Internet.

The goal of the experiment was to predict circular hydraulic jump diameter given a user-set fluid volume flow rate into the jump using measured nozzle diameter and fluid height after the jump. This predicated diameter was then validated by measuring the hydraulic jump diameter directly. Within experimental uncertainty, all theorical and experimental results agreed. This outcome demonstrates the ability of @HOLM™ kits to retain the features, robustness, measurability, and rigor of full-scale brick-and-mortar laboratories currently used in every undergraduate mechanical engineering program. This demonstration is a first step toward complimenting (or entirely replacing) conventional fluid mechanics teaching lab experiments with @HOLM™ kits.

Results from both indirect and direct assessment of student learning outcome attainment measured student performance. 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 felt they learned form it, and they could complete the experimental activities without instructors being physically present.

Hands-on experimental mechanical engineering laboratory kits, which can be mailed to remote learners taking courses on-line, represent a critical new advance in the way undergraduate mechanical engineering curricula are delivered to students. Using @HOLM™ experiments, lab-intensive undergraduate mechanical engineering courses can be taught fully online. 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 follow.

A. Next Steps

Data from indirect and direct assessments revealed some opportunities for future improvement in data collection techniques related to evaluating @HOLM™ experiments. It is possible students scored the indirect assessment survey questions artificially high. However, there was no baseline for comparison. So, in the future, indirect assessment of remote (or simulated remote) teaching lab activities must always be accompanied by an analogous brick-and-mortar control (following Corter and colleagues [15, 16]) to provide an accounting baseline for external variables that could skew results – like student self-selection.

For future direct assessment data collection, the remote (or simulated remote) exercise cannot be an extra credit assignment. It must be a required and graded component of the course. This study relied on voluntary student participation in an extra credit assignment. This recruitment approach could have favored stronger students who would naturally gravitate toward extra credit opportunities. Since we didn't make the @HOLM™ lab activity required for all students enrolled in fluids, we cannot tell if strong direct assessment outcomes result from participation self-selection by strong students gravitating toward extra credit.

Finally, future assessments of this or similar engineering teaching laboratory for online learners should occur with true remote learners to eliminate any effects caused by the simulated online lab experience being offered in a conventional brick-and-mortar teaching space, as was the case here.

REFERENCES

[1] M. Reynolds, "The Emergence of the Online Master's Degree," *Journal of Online Engineering Education,* vol. 2, no. 1, 2011.

[2] "Listing of Online Engineering Programs Accredited by ABET," [Online]. Available: https://www.abet.org/accreditation/find-programs/. [Accessed 16 5 2019].

[3] [Online]. Available: https://und.edu/programs/mechanical-engineering-bs/how-online-works.html.

[4] S. Badjou and R. Dahmani, "Current Status of Online Science and Engineering Education," *Journal of Online Engineering Education,* vol. 4, no. 1, 2013.

[5] F. Fisher, S. K. Esche, R. Ubell and C. Chassapis, "Feasibility Of A Fully Online Undergraduate Mechanical Engineering Degree For Non Traditional Learners," in *Proceedings of the 114th Annual Conference & Exposition,* Honolulu, Hawaii, USA, 2007.

[6] J. Starks, F. R. Hendrickson, F. Hadi and M. J. Traum, "Miniaturized Inexpensive Hands-On Fluid Mechanics Laboratory Kits for Remote On-Line Learning," in *Proceedings of the 124th American Society for Engineering Education (ASEE) Conference and Exposition,* Columbus, OH, 2017.

[7] P. E. Blosser, "The Role of the Laboratory in Science Teaching," *Research Matters to the Science Teacher,* no. 9001, 1990.

[8] F. L. Forcino, "The importance of a laboratory section on student learning outcomes in a university introductory Earth Science course," *journal of Geoscience Education,* vol. 61, no. 2, pp. 213-221, 2013.

[9] A. Hofstein and V. N. Lunetta, "The laboratory in science education: Foundations for the twenty-first century," *Science Education,* vol. 88, no. 1, pp. 28-54, 2004.

[10] A. Hofstein and R. Mamlok-Naaman, "The laboratory in science education: the state of the art," *Chemistry Education Research and Practice,* vol. 8, no. 2, pp. 105-107, 2007.

[11] L. D. Feisel and A. J. Rosa, "The role of the laboratory in undergraduate engineering education,," *Journal of Engineering Education,* vol. 94, no. 1, pp. 121-130, 2005.

[12] "Engineering Criteria 2000," ABET, Baltimore, MD, 2002.

[13] [Online]. Available: https://www.abet.org/accreditation/accreditation-criteria/criteria-for-accrediting-engineering-programs-2019-2020/.

[14] J. Ma and J. V. Nickerson, "Hands-on, simulated, and remote laboratories: A comparative literature review,”," *ACM Computing Surveys (CSUR),* vol. 38, no. 3, 2006.

[15] J. E. Corter, J. V. Nickerson, S. K. Esche, C. Chassapis, S. Im and J. Ma, "Constructing Reality: A Study of Remote, Hands-on and Simulated Laboratories," *ACM Transactions on Computer-Human Interaction,* vol. 14, 2007.

[16] J. E. Corter, S. K. Esche, C. Chassapis, J. Ma and J. V. Nickerson, "Process and learning outcomes from remotely-operated, simulated, and hands-on student laboratories," *Computers & Education,* vol. 57, no. 3, pp. 2054-2067, 2011.

[17] L. D. Feisel, "Private Communication," February 2017.

[18] P. Ranganathan and K. Nygard, "A Tool to Teach Remote Engineering Laboratories," *Journal of Online Engineering Education,* vol. 1, no. 1, 2010.

[19] Y. Astatke, J. Ladeji-Osias, C. J. Scott, K. Abimbola and K. Conner, "Developing and Teaching Sophomore Level Electrical Engineering Courses Completely Online,," *Journal of Online Engineering Education,* vol. 2, no. 2, 2011.

[20] C. Berry, "Lessons Learned Teaching Electrical Circuits Online," *Journal of Online Engineering Education,* vol. 6, no. 2, 2015.

[21] "Stony Book University, Electrical Engineering Online B.S. program," [Online]. Available: http://www.stonybrook.edu/eeonline/. [Accessed 11 2 2017].

[22] "EEO352: Electronics Laboratory I Syllabus," [Online]. Available: http://www.stonybrook.edu/eeonline/docs/EEO352.pdf. [Accessed 11 2 2017].

[23] "EEO353: Electronics Laboratory II Syllabus," [Online]. Available: http://www.stonybrook.edu/eeonline/docs/EEO353.pdf. [Accessed 11 2 2017].

[24] X. Liu and J. H. Lienhard V, "The hydraulic jump in circular liquid impingement and in other thin films.," *Experiments in Fluids,* vol. 15, pp. 108-116, 1993.

[25] Y. Brechet and Z. Néda, "On the circular hydraulic jump," *American Journal of Physics,* vol. 67, no. 8, pp. 723-731, 1999.

[26] J. W. M. Bush, J. M. Aristoff and A. E. Hosoi, "An experimental investigation of the stability of the circular hydraulic jump," *Journal of Fluid Mechanics,* vol. 558, pp. 33-52, 2006.

[27] C. Ellegaard, A. Hansen, A. Haaning, K. Hansen, A. Marcusson, T. Bohr, J. Hansen and S. Watanabe, "Polygonal hydraulic jumps," *Nonlinearity,* vol. 12, p. 1–7, 1999.

[28] A. R. Kasimov, "A stationary circular hydraulic jump, the limits of its existence and its gasdynamic analogue," *Journal of Fluid Mechanics,* vol. 601, pp. 189-198, 2008.

[29] M. Passandideh-Fard, A. R. Teymourtash and M. Khavari, "Numerical study of circular hydraulic jump using volume-of-fluid method," *Journal of Fluids Engineering,* vol. 133, no. 1, p. 011401, 2011.

[30] C. D. Richards, M. F. S. Meng, B. J. Van Wie, P. B. Golter and R. F. Richards, "Implementation of Very Low-Cost Fluids Experiments to Facilitate Transformation in Undergraduate Engineering Classes,," in *Proceedings of the 122nd ASEE Annual Conference and Exposition*, Seattle, WA, 2015.

[31] G. Recktenwald and R. Edwards, "Using Simple Experiments to Teach Core Concepts in the Thermal and Fluid Sciences," in *Proceedings of the 114th ASEE Annual Conference and Exposition*, Honolulu, Hawaii, 2007.

[32] G. Recktenwald, R. Edwards, D. Howe, J. Faulkner and C. Hsieh, "The Engineering of Everyday Things: Simple experiments for the thermal and fluid sciences," in *Proceedings of the 116th ASEE Annual Conference and Exposition*, Austin, TX, 2009.

[33] D. M. Bunce, E. A. Flens and K. Y. Neiles, "How Long Can Students Pay Attention in Class? A Study of Student Attention Decline Using Clickers," *Journal of Chemistry Education, Volume, Number,* vol. 87, no. 12, p. 1438–1443, 2010.

[34] A. Shirmohammadi and A. Johnson, "Experiences with Group Work at the University of Maryland - In Noir," in *Proceedings of the 113th ASEE Annual Conference and Exposition*, Chicago, IL, 2006.

AUTHORS

M. J. Traum is founding CEO at the STEM education social enterprise company Engineer Inc, Gainesville, FL, USA 32653 (e-mail: CEO@EngineerInc.net). Most recently, Dr. Traum was an Associate Professor and Director of Engineering Programs at Philadelphia University. He was previously an assistant professor of mechanical engineering at the Milwaukee School of Engineering and a founding faculty member and assistant professor in the Mechanical & Energy Engineering Department at the University of North Texas – Denton. Traum earned his Ph.D. in mechanical engineering from the Massachusetts Institute of Technology where he held a research assistantship at MIT’s Institute for Soldier Nanotechnologies.

F. Hadi is an assistant professor in the Department of Mechanical and Manufacturing Engineering at Tennessee State University, Nashville, TN, USA 37209 (e-mail: fhadi@tnstate.edu). She received her Ph.D. in mechanical engineering at Northeastern University, working on topics in chemical kinetics dimension reduction, turbulent reacting flow, computational fluid dynamics, large eddy simulation, and high-performance computing.

Submitted, May 26, 2019. Published as resubmitted by the authors on May XX, 2019.