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Development And Evaluation of a Mass Conservation Laboratory Module in a Microfluidics Environment

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ABSTRACT

Laboratory-based instruction is a powerful educational tool that engages students in Science, Technology, Engineering and Mathematics (STEM) disciplines beyond textbook theory. This is true in mechanical engineering education and is often used to provide collegiate-level students a hands-on alternative to course theory. Module-based laboratory instruction allows students to investigate fundamental concepts interactively and often affords new critical thinking skills and technical aptitude.

The authors have developed a novel mass conservation laboratory module for use in undergraduate fluid mechanics education via module-based instruction. The module investigates mass conservation fundamentals in a simple microfluidic T-junction device. The experiment is a novel application of microfluidics-based instruction, is highly repeatable, and can be conducted at relatively low cost. The module exposes students to the rapidly developing field of microfluidics and allows them to gain familiarity with fluorescence-based optical diagnostics and simple signal processing.

In addition, this study quantifies the module's educational impact on thirty-six mechanical engineering undergraduates. A baseline study was conducted by utilizing knowledge assessments before and after the experimental module. The results of the study are statistically significant and suggest the module's efficacy for teaching mass conservation fundamentals in an undergraduate curriculum.

Key Words: Laboratory, fluid mechanics, mass conservation

INTRODUCTION

Laboratory-based learning is hugely important for effective education in Science, Technology, Engineering and Mathematics (STEM) disciplines (Elliott, Stewart, and Lagowski 2008; Jewell 2008; Fintschenko 2011). This is especially true for engineering studies, and is argued that effective engineering education programs must feature some manner of hands-on laboratory-based education (Krivickas 2007). The gravity and importance of lab-based work stems from the Accreditation Board of Engineering and Technology (ABET's) selection of thirteen lab curriculum objectives meant to guide the engineering educator (Rosa 2005). These objectives seek to develop students in many areas, including design and testing, instrumentation, experimentation, data analysis and modeling, and communication and teamwork skills. These skills afford the engineering student an educated advantage in the professional or academic setting, as they enable students to effectively confront "real world" engineering problems (Fintschenko 2011).

Laboratory-based education is often accomplished through the use of small teaching lessons or modules, as compared to the continuous style of lecture-based learning. Instruction modules are becoming increasingly amenable to the learning style of today's Millennial students, who tend to be sheltered, confident, team-oriented and high achieving (Howe and Strauss 2000). As such, students can benefit from division of the curriculum into more manageable, interactive pieces (Wilson and Gerber 2008) which provide a more experiential, small group sized, action and reflection learning experience amenable to these personality traits. The primary benefit of utilizing module-based learning in a laboratory setting stems from its amenability to the "active learning" methodology. Felder and colleagues have found active learning allows students the opportunity to see the application of methods through an instructor and apply the methods themselves, while also being given an opportunity to reflect on outcomes at the end of the application (Felder, Brent, and Prince 2011). This use of action and reflection is often referred to as praxis and is becoming widely recognized in learner-centric education techniques. In laboratory-oriented education, this is most easily accomplished through the series of a pre-lab, laboratory experimentation, and post-lab write up. Small group sizes, four to five students, also facilitate the teamwork and communication objectives identified by ABET.

In 2000, the Mechanical Engineering department at The University of Texas at Austin developed a "department-wide curriculum reform effort, with the objective of more closely tying all elements of the Mechanical Engineering undergraduate experience to real-world engineering" (Schmidt and Beaman 2003). This reform effort, known as Project Centered Education in Mechanical Engineering (PROCEED), has funded a wide spectrum of curriculum and laboratory development projects for the past 13 years. In 2012, ME 130L: Experimental Fluid Mechanics was selected for PROCEED funding to continue development of a module-based educational program in laboratory-oriented education for a mass conservation laboratory module. This funding was granted, in no small part, due to previous work in integrating module-based education with wind energy technology in ME 130L (Sheble, Bickle, and Hidrovo 2013).

The research presented in this article aims to demonstrate and evaluate a novel microfluidics-based laboratory module. The module is designed to teach continuity fundamentals via fluid flow regimes present in microfluidic systems. This unique case offers students insight into the ubiquity of the continuity equation.

BACKGROUND: MASS CONSERVATION AND TWO-PHASE FLOW

Microfluidics is “the controlled transport and manipulation of liquid solutions, suspensions, or microscopic objects in a volume regime of about 1 femtolitre to microliters” (Fintschenko 2011), and offers a unique educational perspective for mass conservation education. Educational microfluidics has been used to investigate chemical titration (Greener et al. 2012), tissue rheology (Young and Simmons), crystallization phenomena (Chia et al. 2011), and has substantial potential for fluid mechanics education. However, using a microfluidic system to teach mass conservation fundamentals is a novel application and has not been demonstrated in research to date. This research utilizes microfluidic plug flow (Garstecki et al. 2006) as a teaching mechanism, as the physics that drive the plug flow regime offer unique insight into the laws of continuity.

In plug flow, two immiscible phases are injected into a microchannel device to form alternating plugs of fluid. Aptly named, these plugs span the width of the microchannel. This behavior forces the two phases to translate at the same velocity while inside the microchannel. The characteristic plug velocity is a result of the input mass flow rates and can be predicted based on the laws of continuity. Many architectures exist for plug generation in microfluidic devices, including electromotive systems (Pollack, Shenderov, and Fair 2002; Link et al. 2006), acoustic generation of droplets (Elrod et al. 1989), and flow-focusing devices (Anna, Bontoux, and Stone 2003). However, T-junction architectures offer similar capabilities (Garstecki et al. 2006) while being less complex than the flow-focusing alternative. In addition, the photolithography and soft lithography processes required to fabricate multiple “lab-on-a-chip” devices (Fujii 2002) are simplified with basic channel designs. Given the need to have clean microfluidic devices for each lab group, T-junction architectures were chosen for this experiment (Figure 1).

The advantage for utilizing microfluidic plug flow for mass conservation analysis stems from two sources: (a) the plug velocity of the two immiscible phases are interlinked and equal, and (b) a

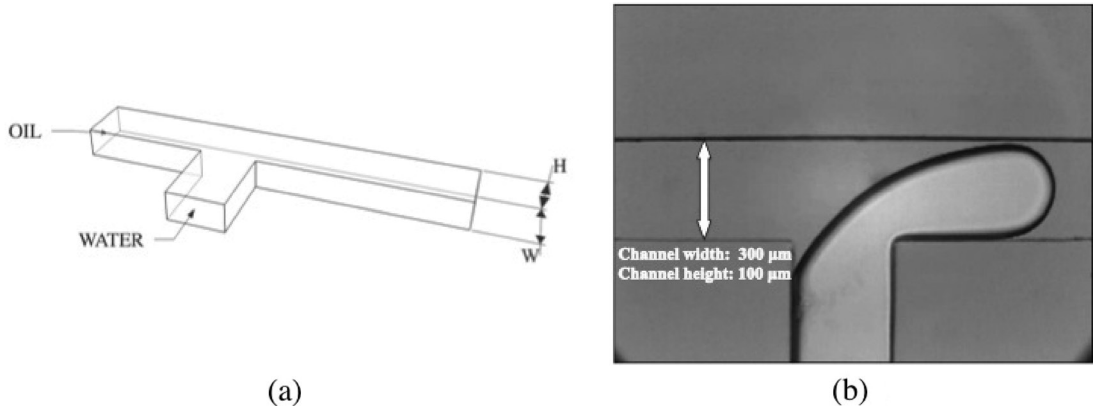

Figure 1. (a) Schematic of the T-junction microfluidic channel. The microchannels have uniform height, H, and width, W. (b) The continuous phase (here 'oil') and the dispersed phase (here 'water') are immiscible. Flowing these fluids into their respective oil and water ports will create alternating plugs of fluid downstream of the microchannel T-junction. The channels have a nominal height and width of 100 x 300 µm.

regularly cyclic flow pattern can be observed downstream of the junction (once steady-state flow is achieved). This cyclic flow pattern allows the experimentalist to measure two key parameters of interest: (a) the plug velocity, and (b) the flow fraction of water vs. oil (to be later defined as the "duty cycle"). The goal of this experiment is to allow students to measure both the plug velocity and flow fraction for a constant mass flow rate experiment. Students investigate the relationship between the duty cycle and the plug velocity and compare it to a theoretical model they derive through the laws of mass conservation. Video media, available through https://youtu.be/4hMptohYCaQ, displays a visualization of the channel found in Figure 2.

Conservation of mass in a steady-state system dictates that all mass flow into the microfluidic device sums to zero. Therefore, if the inputs for oil and water are known the output of the system can be inferred (Eq. 1). The mass flow rate into the device depends on the volumetric flow rates of oil and water to the device, and their respective fluid densities (Eq. 2).

$$\dot{m}_{in} = \dot{m}_{out} = \dot{m}_{total} = \dot{m}_w + \dot{m}_o \quad \text{Eq. 1}$$

$$\dot{m}_{total} = \rho_w Q_w + \rho_o Q_o \quad \text{Eq. 2}$$

The plug flow phenomena links the velocity of the downstream oil and water plugs together. This common velocity, referred to as V_{plug}, provides direct insight into the mass flow rate of the

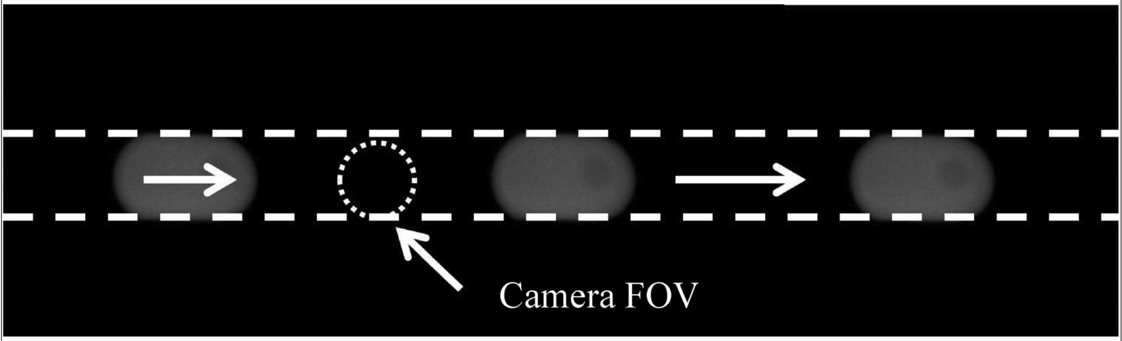

Figure 2. Microfluidic plug flow is generated with oil and fluorescing water and imaged via epi-fluorescence. Students will investigate a region of interest downstream of the device junction in order to generate a photo-response signal. This signal can be used to prove the microfluidic device's adherence to mass conservation laws.

microfluidic system. Mass conservation equalities for both oil and water mass flow rates (Eq. 4 and Eq. 5) are derived through combining the plug velocity with the flow-fraction parameter, which is defined as the volumetric portion of the flow that is composed by water, as depicted in Figure 3. This flow fraction parameter offers insight into the size and spacing of the water plugs.

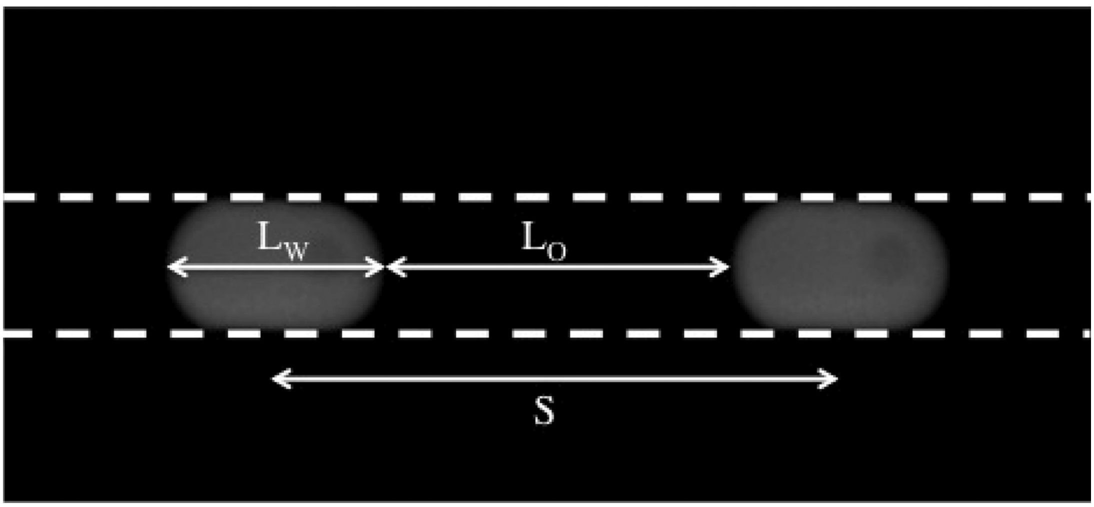

Figure 3. The size of water plugs, Lw, and the spacing of water plugs (consequently the size of the oil plugs), Lo, can be used to establish a parameter for measuring the cyclic water plug flow fraction. This parameter requires the total length of the oil and water plug, S, to remain constant throughout flow rate measurement.

The flow-fraction parameter (Eq. 3) and the characteristic plug velocity are both used to derive continuity equations for oil and water flow rates. This fully defines the flow rates into and out of the microfluidic device.

$$F = \frac{L_w}{S} = \frac{L_w}{L_o + L_w} \qquad \text{Eq. 3}$$

$$\dot{m}_w = \rho_w A V_{plug} * F \qquad \text{Eq. 4}$$

$$\dot{m}_o = \rho_w A V_{plug} * (1 \rho F) \qquad \text{Eq. 5}$$

Given these equations, it is possible to derive a relationship between the relative fractions of water to oil and the total plug velocity. This requires students to investigate the relationship between flow fraction and plug velocity under constant mass flow rate, i.e. varying inlet oil and water flow rates in such a manner that the total inlet mass flow rate remains constant during experimentation. Students will derive Eq. 6 and investigate its parameters, including effects caused by changes in channel dimensions, relative fluid densities, and changes in the flow fraction parameter F. This change in the flow fraction parameter is accomplished by varying the ratio of the oil-to-water flow rates such that constant mass flow rate is maintained.

$$V_{plug} = \frac{1}{A} \; \frac{\dot{m}_{in}}{[\rho_w - \rho_o]F + \rho_o} \qquad \text{Eq. 6}$$

LAB MODULE SETUP

Fluorescence Microscopy

Fluorescence microscopy is an ideal technique for microfluidic velocimetry, given that it is non-invasive and consequently will not disrupt the fluid flow. Polydimethylsiloxane-based (PDMS) microchannels are advantageous in fluorescence-based detection (Fujii 2002) since PDMS is highly transparent across the visible spectrum. Similarly, the plug flow regime formed by the immiscible oil and water is also beneficial, as these fluids are easily discernable through the fluorescence microscopy by introducing a dye into the water.

As outlined by Reichman, fluorescence microscopy requires the use of a dichroic filter cube to match the dye chosen for the experiment (Reichman 2010). In this case, Fluorescein-548 was paired with a blue-green dichroic filter available through the microscope manufacturer. The dichroic filter reflects the blue light source onto the specimen containing Fluorescein-548, and causes the dye to fluoresce green light due to the Stokes shift (Figure 4). This green light is transmitted through the dichroic filter and visualized by the scientist (Figure 5).

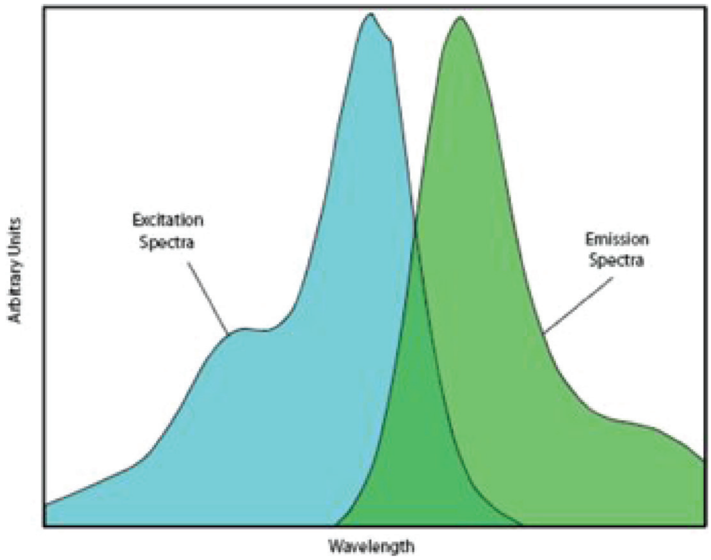

Figure 4. The dichroic filter cube reflects shorter wavelength light (higher frequency) and transmits longer wavelength light. This capability is paired with a fluorescent dye specimen whose Stokes shift matches the dichroic filter cube (Image via Reichman, 2010).

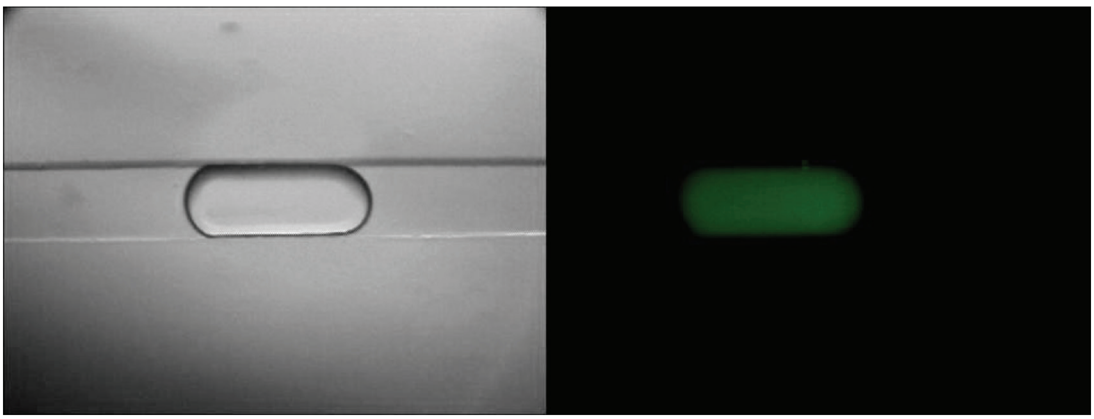

Figure 5. Imaging in bright field (left) and epi-fluorescence (right) downstream of the T-junction demonstrates the benefit of the fluorescent dye. Introduction of the fluorochrome into the water allows the experimentalist to optically distinguish the presence of oil or water inside the microchannel via wide-field fluorescence microscopy. This method is non-invasive and will not disrupt the plug flow behavior inside the microfluidic device. The microscope probes a region smaller than the plug length. This Eulerian approach allows the experimentalist to probe the regularly cyclic flow generated by the device.

Signal Processing

The MATLAB scripts used for the signal processing are available for public use on GitHub. They can be found at https://github.com/alfacharliekilo/microfluidic_mdot.

The measured light intensity inside the camera's detector region of interest (ROI) varies cyclically due to the plug flow phenomena. Images are recorded via CCD camera and processed with MATLAB script. For each image, the output signal from the code is proportional to the portion of the ROI that is illuminated by fluorescence light intensity. Each pixel in the ROI is made binary (ON-OFF) by setting an illumination detection threshold value (see Figure 6). If the signal-to-noise ratio of a pixel's light intensity is greater than the detection threshold (i.e. background noise of the camera), the script counts the pixel as ON, otherwise it's assumed to be OFF. The total signal is equal to the sum of "active" (ON) pixels in the ROI of the camera.

The plug flow fluorescence signals provide two types of information: (a) downstream velocity of the oil and water plugs and (b) relative fractions of oil and water. Signal vs. time, shown in Figure 7 (left), varies cyclically and the rise time is non-instantaneous. This is a consequence of the water plug moving across the detector boundary. Given the dimensions of the detector and known pixel resolution, it is possible to calculate the plug velocity of both the oil and water. This is accomplished through Eq. 7, where L_{det} represents the detector size (in pixels), R represents the pixel resolution, and T represents the time required to transition from a fully "OFF" signal to a fully "ON" signal.

$$V_{plug} = \frac{RL_{det}}{T} \qquad \text{Eq. 7}$$

Figure 6. The "eye" of the MATLAB script (white slot, shown left) counts active pixels based on the light intensity of the plug inside this "eye". The signal (shown right) is the sum of all "active" pixels in the camera's detector region of interest (ROI).

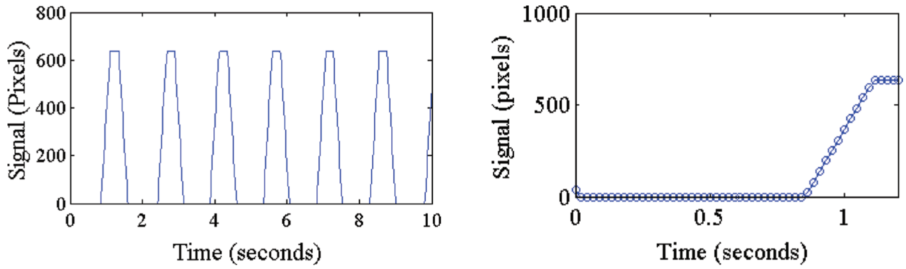

Figure 7. The signal rise time (shown right) gives key information about the oil and water plug velocities, which are equal due to plug flow physics.

The lab module utilizes a signal parameter, D, known as the "duty cycle" (Eq. 8). It is a measure of the flow fraction F from Eq. 3. The duty cycle is a tool to gauge the fluorescence fraction of the plug flow and is therefore a measure of the flow rate fraction of water to oil. The duty cycle tends towards a value of 1 as the flow rate fraction of water-to-oil increases. A duty cycle of 0 indicates no signal and a flow fraction of 0, meaning that the whole flow is only composed of oil. The plug velocity can then be calculated as function of total mass flow rate, water and oil densities, and the duty cycle (Eq. 9).

$$D = \frac{\tau}{T} \; \frac{trig_3 - trig_1}{trig_5 - trig_1} \qquad \text{Eq. 8}$$

$$V_{plug} = \frac{1}{A} \; \frac{\dot{m}_{in}}{[\rho_w - \rho_o] * D + \rho_o} \qquad \text{Eq. 9}$$

Trigger points within the fluorescence signal are used to determine both the plug velocity and duty cycle (Figure 8).

PROCEDURE

Students will measure both the plug velocity and flow fraction for a constant mass flow rate experiment. Students are to investigate the relationship between the measured duty cycle and the plug velocity and compare it to a theoretical model they derive through the laws of mass conservation.

The mass conservation lab module is intended for three to four students per session and is divided into two stations: operation of the microscope equipment and pumps, and operation of the video acquisition software and MATLAB processing scripts (Figure 9). Shown in Table 1, the equipment required to run the lab can be purchased for about $7,000. This cost depends on the selection of

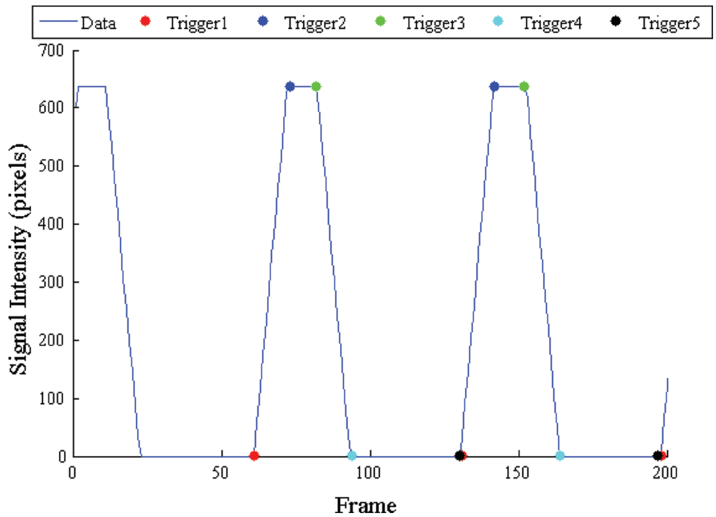

Figure 8. Trigger points mark the transition boundary between ON and OFF and allow for calculation of the plug velocity and flow rate fraction.

an appropriate inverted epi-fluorescence microscope system and can be substantially reduced if one is built in-house rather than buying an off-the-shelf system.

Students are to use a clean microfluidic device for their experiment. Prior to experimentation, a lab assistant will ensure that the syringes and lines are purged of air. Introduction of gas into the microfluidic device will introduce error in the plug flow measurements.

Item	Quantity	Description	Estimated Cost
100 µL Syringe	2	Hamilton Syringe, 1710 Luer Lock Tip, ID 1.457 mm	$140
Syringe Pump	2	New Era Pump Systems, NE-300	$550
Luer Lock Fittings	2	Compression fittings, 1/16” OD	$70
PEEK Tubing	1	Blue 1/16” OD, 0.01” ID, 5 ft	$20
Mineral Oil	1	5 L, SG = 0.86	$50
Span® 20	1	Oil-soluble surfactant, 250 g	$30
Fluorescein-548	1	Water-soluble fluorescent dye, 1 g	$70
Microfluidic T-junction device	1	PDMS-based microchannel mounted on slide glass	—
Epi-Fluorescence Microscope w/ USB Camera	1	SpecialtyMicroscopes.com. 3.2M pixels, ½” chip w/ 3. µm/pix	$6,000
Consumables (Gloves, glass slides, paper towels, IPA for cleaning)	1	1 box of gloves will supply ~100 students	$50
		Expected Cost	~$7050

Table 1. List of materials for mass conservation lab module.

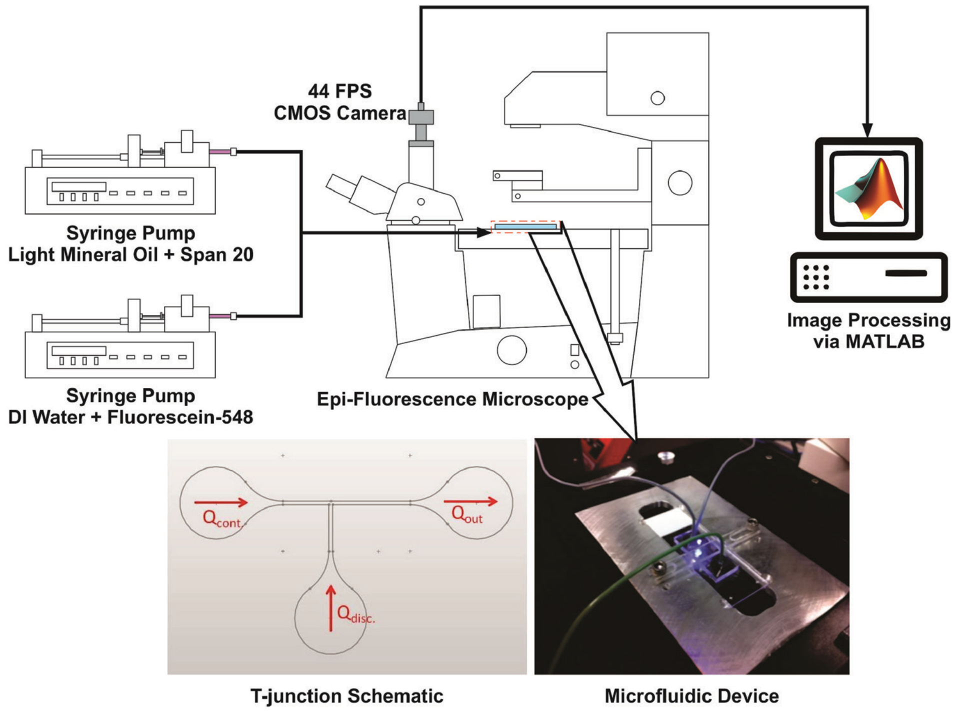

Figure 9. An epi-fluorescence microscope is used with a simple microfluidic device, syringe pumps, and MATLAB image processing scripts to probe the plug velocities of two-phase plug flow. Velocimetry is accomplished by recording plug behavior downstream of the junction and performing image processing in MATLAB.

Oil and water are initially flowed through the device at a rate of 5 QL/min. This purges air out of the microchannel and fills the device with oil and water. Flow rates are reduced to 1 QL/min after all air is purged from the device. At this point, students should visualize the plug formation at the T-junction. Modification of the oil's surface tension through the introduction of Span-20 ensures repeatable plug length, as shown in Figure 10.

The microscope stage should not be moved once the camera is aligned with the microchannel and the microscope is focused. The droplets are very sensitive to changes in inertia and must be steady-state for accurate results.

The lab module has students investigate microchannel plug flow at a constant mass flow rate of 2 mg/min; Table 2 outlines the volumetric flow rates used in this experiment. Each set point should be measured for at least one minute to gather enough signal data. Time for set-up, experimentation and data collection should take 45 minutes to an hour.

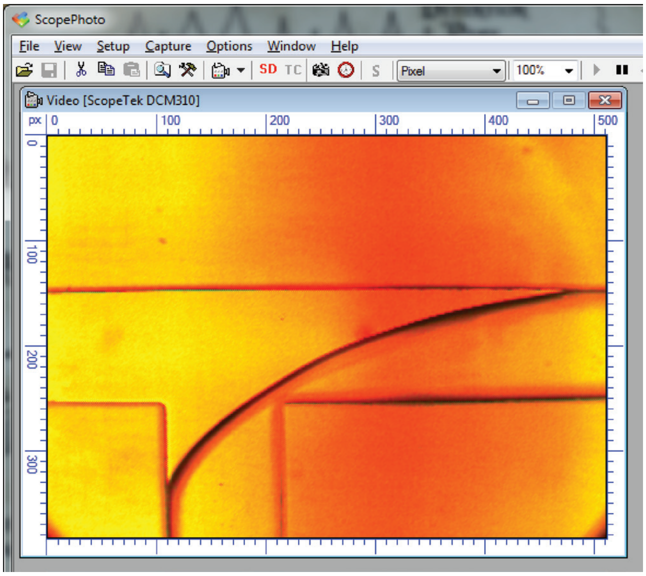

Figure 10. Water plugs must consistently "break" at the 90° junction to ensure that all plugs feature the same characteristic length.

STUDENT EVALUATION

A sample of 36 student volunteers from the Spring 2013 Experimental Fluid Mechanics (ME130L) course from the Mechanical Engineering Department at UT Austin were selected to evaluate the efficacy of the lab module. Students received no additional benefit to their coursework and were not offered incentive to participate beyond their own interest in the material. Evaluation of the lab module was conducted though pre- and post-evaluation student assessments. These benchmarks gauged student knowledge prior to the lab and retention of material after conclusion. Students were

Water Flow Rate (μL/min)	Oil Flow Rate (μL/min)
0.200	2.091
0.400	1.856
0.600	1.627
0.800	1.394
1.000	1.162

Table 2. Syringe pump set points for 2 mg/min total mass flow rate plug flow regime.

Group	Fundamental Principle	Number of Questions
1	Non-dimensional numbers, flow regimes, and plug flow dynamics	8
2	Microscopy and micro-fabrication	5
3	Uncertainty analysis	4
4	Mass conservation	14
5	Signal generation and analysis	4

Table 3. Evaluation test groups and group sizes.

grouped into teams, each team consisting of 3-4 members. The pre- and post-evaluations are based on the same test. The evaluation consists of 24 questions that tested the student's knowledge of the fundamental principles found in Table 3.

A paired, two-sided Student's *t*-test with 35 degrees of freedom and a confidence interval of 95% was used to determine the significant difference of each test group. Cohen's *d* effect sizes were calculated from the results of this test. *P*-values less than 0.05 indicate statistical significance (Mills and Chang 2004) and demonstrates the experiment improved students' understanding and knowledge of the concepts presented. Effect sizes within the range of 1.66 to 1.78 imply 95% confidence on the significance. A 95% confidence interval suggests the experiment substantially improved the students' understanding and knowledge of the concepts presented in it (Cohen 1988). The results from the evaluation benchmark on these two metrics are presented in Table 4. They suggest that although there is statistical significance in terms of knowledge gained over all the fundamental concepts probed in the test (Groups 1 through 5), the magnitude of the improvement is only appreciable or substantial for Groups 1 and 4. In other words, it is clear that the student sample population learned concepts related to fluid mechanics and mass conservation concepts after conducting the laboratory experiment. When considered as a whole, there is also strong evidence of the overall

	p-value	Cohen's difference *d* effect size
Total Assessment	9.8 e-10	1.73
Group 1	2.3 e-12	2.19
Group 2	1.5 e -3	0.67
Group 3	2.2 e -1	0.26
Group 4	1.0 e -8	1.72
Group 5	1.3 e -1	0.39

Table 4. Results of the Student's t-test for statistical significance.

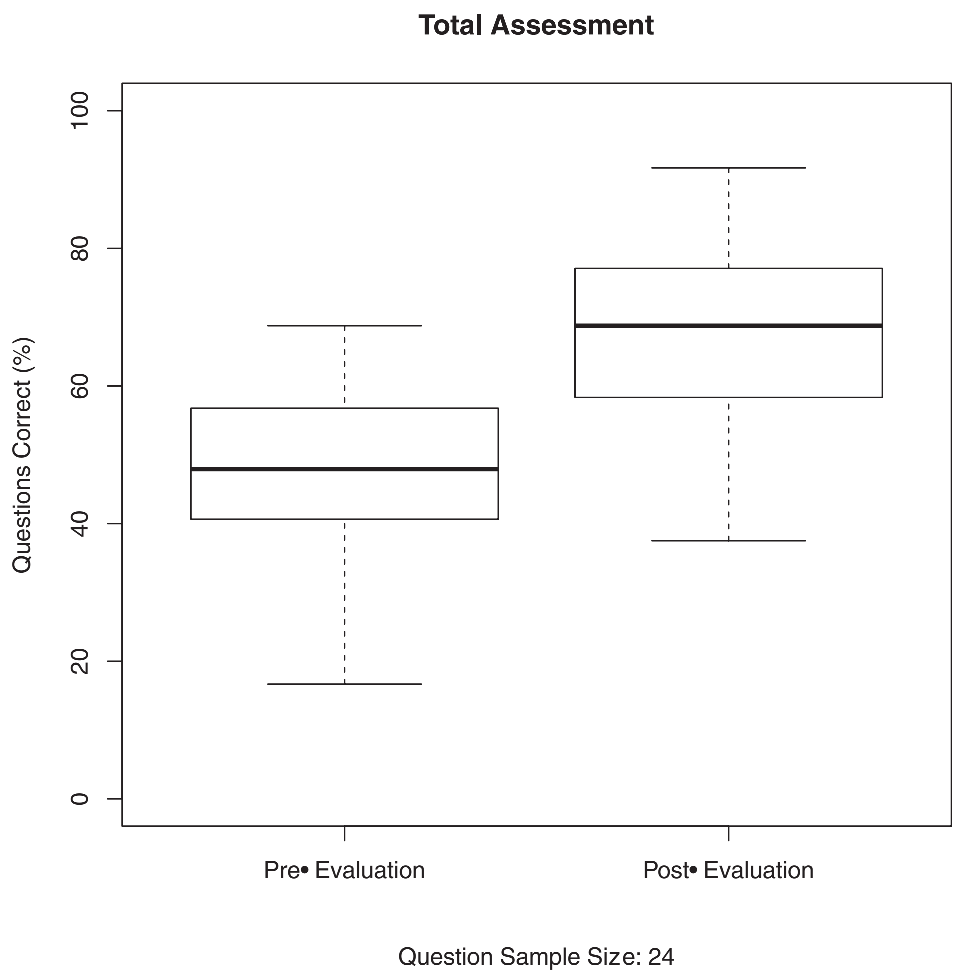

Figure 11. Boxplot of the total student assessment. Post evaluation score averages increased from 48% to 69%.

knowledge gained within the global framework of the test and lab. This is clearly appreciable in Figure 11, which depicts boxplots of the student assessment pre- and post-evaluation. Clearly there is enough separation within the populations' means and the middle quartiles of both populations do not overlap. It should be noted that the relatively small effect sizes of Groups 2, 3 and 5 could be related to the small number of questions posed on these topics.

The Group 1 assessment was used to evaluate the student's understanding of microflu-idics-related non-dimensional numbers (Reynolds and Capillary), flow regimes and regime transitions, as well as basic plug flow physics. The primary goal of the material in this group was to cue students into the relationship between the oil and water flow velocities, in that they are equal in the plug flow regime.

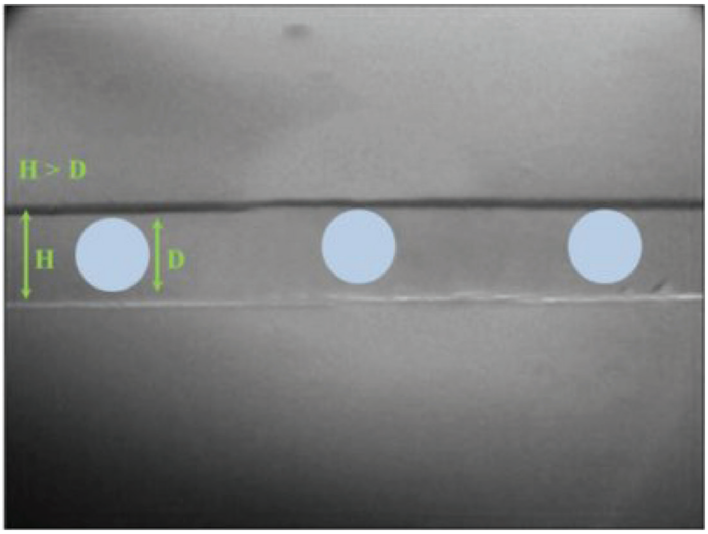

Figure 12. Downstream plugs approach the droplet flow regime as they shrink in sizes smaller than the channel width. It is important for students to recognize that oil and water stream velocities are no longer linked in this regime as oil (water) can flow past the water (oil).

This conclusion is important, as it directly links the signal generated by the microfluidic device to the aforementioned conservation laws. Without this criterion, students would be unable to infer both the oil and water velocities from the light signal alone and could not prove mass conservation in the device. Students were asked to categorize microflows based on the Reynold's number (<0.1) and the Capillary number (< 0.001). In addition, students gained basic exposure to flow regime shifts, namely the transition between the plug flow regime and the "droplet flow" regime shown in Figure 12. The implication of this shift concerns the relative average velocities of oil and water downstream of the T-junction, which are no longer equal. As the water plugs shift to droplets in cross-flow, mass flow rate can no longer be inferred solely from the light signal generated by the water droplets.

Group 2 sought to assess the student's exposure to both epi-fluorescence microscopy and to micro-fabrication techniques like photolithography and soft lithography. Results found students demonstrated understanding of the Stokes shift and properties of PDMS for microfluidics applications. However, more development is needed in these areas to properly assess the extent of the gains achieved by the students.

Group 3 categorized questions related to uncertainty analysis. Questions were crafted to gauge students' understanding of both precision and bias errors and required students to propagate uncertainty with either sequential perturbation or the standard partial-derivative method. By design, the MATLAB-based plug detector returned both a duty cycle and plug velocity for each oil-water plug couple. This returned anywhere from 30-50 plug detections per video recording, allowing students to generate a precision uncertainty for both the duty cycle and the plug velocity. Students were not required to perform syringe pump calibration in this experiment; however, doing so provides more practice in uncertainty analysis. Calibration requires students to grasp concepts such as standard error for curve fits, precision vs. bias uncertainty, and uncertainty of sample means vs. uncertainty of single measurements. A sample syringe pump calibration is shown below in Figure 13. 10 independent measurements at each flow rate set point were made to obtain the calibration curve. During the lab procedure, students were asked to obtain 10 or more independent measurements at each set point and then average their results. As such, the total uncertainty of the fit (i.e., uncertainty of the mean), rather than the uncertainty of a single measurement, is the proper metric to use when assessing the 95% confidence interval of their results. Total (bias and precision) mean measurement and single measurement uncertainties are included and presented in the figure (Mills and Chang, 2004). Students are led to infer that syringe pumps can introduce large

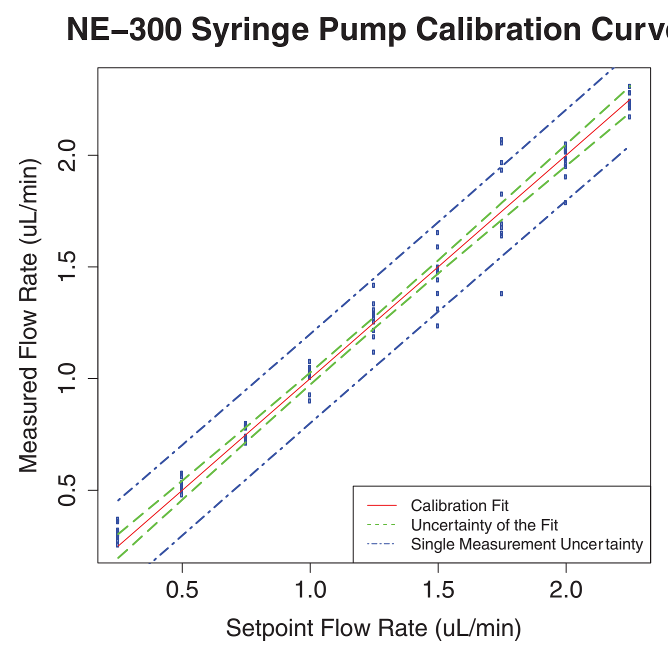

Figure 13. Syringe pump calibration yields maximum mean uncertainty of 3 0.05 QL/ min at the 0.25 QL/min set point. The instructor should use this result to teach students the necessity of calibrating equipment prior to running experiments.

precision errors as the stepper motor and screw drive that push the syringes cause flow rates to substantially fluctuate. However, they would also conclude that by taking several samples and averaging their results the effect of these fluctuations on their results could be minimized. As a secondary point, students would also conclude that syringe pumps might not be ideal for specific low-flow applications.

Group 4 constitutes the largest component of the student evaluation and was intended to assess student learning of mass conservation principles in the microfluidics environment. The results shown in Table 4 suggest that the lab module did indeed convey mass conservation fundamentals to the volunteer student group. Students were required to understand the relationship between the syringe pump set points and the plug velocities. Since water is denser than oil, increases in the water-to-oil volumetric flow rate fraction cause a net decrease in the plug velocity, as per Eq. 9. This is a direct effect of the conservation of mass and will hold as long as the plug flow regime with equal water and oil velocities is maintained. In addition, students were also asked to derive this same mass conservation equation for the plug flow regime velocity. This equation depends on both the total mass input rate and the difference in density between the continuous oil phase and the dispersed water phase, see Eq. 6. As shown in Figure 14, utilizing a low-density mineral oil (red curve as compared to blue curve) results in more drastic changes in velocity (i.e., more non-linear) with varying duty cycle. Increasing (or decreasing) the total input mass flow rate will cause the curve to translate up (or down). The blue curve features a higher total input mass flow rate than the red curve. Increasing the difference between the densities of the continuous and dispersed phase, shown in Eq. 6, causes a higher velocity sensitivity to changes in the duty cycle. The red curve features a larger difference between continuous and dispersed phase density than the blue curve.

CONCLUSION AND FUTURE WORK

Laboratory-based learning serves as a powerful active learning tool that engages engineering students well beyond classroom materials. Module-oriented instruction excels as an educational laboratory framework by utilizing small groups and scope-limited activities. The primary goals of this mass conservation active learning laboratory module were to improve student understanding of mass conservation fundamentals and to introduce mechanical engineering students to the growing field of microfluidics and optical diagnostics. To accomplish these goals, a robust laboratory procedure was developed and an extensive assessment was implemented for a sample of thirty-six mechanical engineering undergraduates.

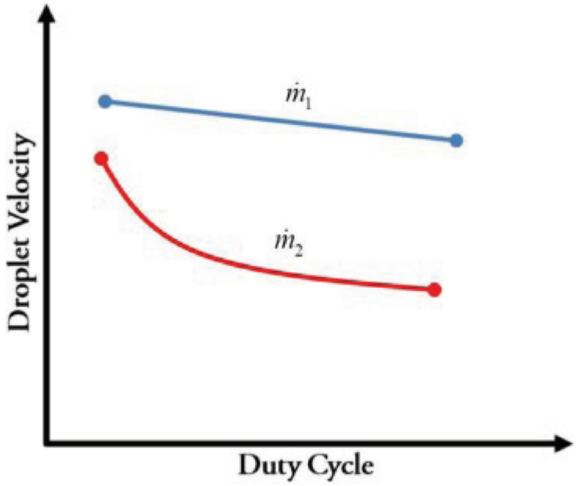

Figure 14. High total mass flow rate, low density difference (1) and low mass flow rate, high density difference (2) plug velocity versus duty cycle (water flow rate fraction) curves. The plug velocity is linear with the total mass flow rate, meaning that larger values of the latter lead to an upper shift of the curve. The dependence of plug velocity with density difference between water and oil is more complicated but in essence larger values of this difference lead to more non-linear behavior with duty cycle (for reference, equal water and oil densities would result in a constant plug velocity or "flat" curve).

Development of the lab module required proper epi-fluorescence imaging equipment. The optics, image acquisition equipment, and image processing equipment are included here. MATLAB, or similarly LabVIEW, can be used for image processing and signal generation. The demonstrated advantage of this setup, beyond its student learning impact, is found in its low cost. A budget of $7,000 would easily and readily duplicate the findings outlined above.

The results of the statistical comparison between the pre- and post-evaluations shown in Table 4 suggest that the lab module had a notably positive impact on student learning of plug flow physics and the mass conservation concept. Based on these results, it is reasonable to claim that this novel laboratory module succeeds in conveying mass conservation fundamentals to undergraduate mechanical engineering students and has the added benefit of introducing students to a field of microfluidics and optical diagnostics that is beyond the current mechanical engineering curriculum.

Presenting the mass conservation experiment in a lab-on-a-chip environment allows the student to reconsider the continuity fundamentals taught in lecture. Simply put, the students use the lab experiment to apply the continuity equations that are taught at the macro-scale in a micro-scale system to analyze its behavior. This unique use of active learning allows the student the opportunity to use in-class (macro-scale) methods and apply them to the experiment in the micro-scale and prove that mass conservation is indeed ubiquitous and independent of scales. In addition, by using the lab-based instruction module, continuity fundamentals can be made more amenable to the learning style of today's "Millennial" student. This is accomplished with the division of the in-class curriculum into a smaller and more focused lab modules.

More laboratory time may be required to allow the students to gain more exposure to the droplet detection system. Adapting the signal detection MATLAB scripts to detect droplets in real time, as opposed to the current method that processes recorded videos, would give students direct exposure to the variation of plug velocity with duty cycle and inlet flow conditions. This could be accomplished in conjunction with the pre-lab materials, along with a more in-depth teaching assistant lecture over statistics and uncertainty analysis fundamentals.

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REFERENCES

Anna, Shelley L., Nathalie Bontoux, and Howard a. Stone. 2003. "Formation of Dispersions Using 'flow Focusing' in Microchannels." *Applied Physics Letters* 82 (3): 364. doi:10.1063/1.1537519. http://link.aip.org/link/APPLAB/v82/i3/p364/s1&Agg=doi.

Carroll, Brian, and Carlos Hidrovo. 2012. "Droplet Collision Mixing Diagnostics Using Single Fluorophore LIF." *Experiments in Fluids* 53 (5) (August 19): 1301–1316. doi:10.1007/s00348-012-1361-x. http://link.springer.com/10.1007/s00348-012-1361-x.

Chia, Matthew C, Christina M Sweeney, United States, and Teri W Odom. 2011. "Chemistry in Microfluidic Channels" 88 (4): 461–464.

Cohen, Jacob. 1988. *Statistical Power Analysis for the Behavioral Sciences* (second ed.)

Elliott, M J, K K Stewart, and J J Lagowski. 2008. "The Role of the Laboratory in Chemistry Instruction" 85 (1): 145–149.

Elrod, S. a., B. Hadimioglu, B. T. Khuri-Yakub, E. G. Rawson, E. Richley, C. F. Quate, N. N. Mansour, and T. S. Lundgren. 1989. "Nozzleless Droplet Formation with Focused Acoustic Beams." *Journal of Applied Physics* 65 (9): 3441. doi:10.1063/1.342663. http://link.aip.org/link/JAPIAU/v65/i9/p3441/s1&Agg=doi.

Felder, Richard M. (North Carolina State University), Rebecca Brent, and Michael J. (Bucknell University) Prince. 2011. “Engineering Instructional Development : Programs , Best Practices , and.” *Journal of Engineering Education* 100 (1): 89–122.

Fintschenko, Yolanda. 2011. “Education: A Modular Approach to Microfluidics in the Teaching Laboratory.” *Lab on a Chip* 11 (20) (October 21): 3394–400. doi:10.1039/c1lc90069b. http://www.ncbi.nlm.nih.gov/pubmed/21909517.

Fujii, Teruo. 2002. “PDMS-Based Microfluidic Devices for Biomedical Applications” 62: 907–914.

Garstecki, Piotr, Michael J Fuerstman, Howard a Stone, and George M Whitesides. 2006. “Formation of Droplets and Bubbles in a Microfluidic T-Junction-Scaling and Mechanism of Break-Up.” *Lab on a Chip* 6 (3) (March): 437–46. doi:10.1039/b510841a. http://www.ncbi.nlm.nih.gov/pubmed/16511628.

Greener, Jesse, Ethan Tumarkin, Michael Debono, Andrew P Dicks, and Eugenia Kumacheva. 2012. “Education: A Microfluidic Platform for University-Level Analytical Chemistry Laboratories.” *Lab on a Chip* 12 (4) (February 21): 696–701. doi:10.1039/c2lc20951a. http://www.ncbi.nlm.nih.gov/pubmed/22237720.

Heywood, John. 2005. *Engineering Education: Research and Development in Curriculum and Instruction*. Edited by Mohamed E. El-Hawary. Piscataway, NJ: IEEE Press.

Howe, Neil, and William Strauss. *Millennials Rising: The next Great Generation /by Neil Howe and Bill Strauss ; Cartoons by R.J. Matson.* New York: Vintage, 2000. Print.

Jewell, Ward T. 2008. “The Importance of Laboratory Experience in Power Engineering Education.” *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century* (July): 1–2. doi:10.1109/PES.2008.4596491. http://ieeexplore.ieee.org/lpdocs/epic03/wrapper.htm?arnumber=4596491.

Krivickas, Romanas V. 2007. “Laboratory Instruction in Engineering Education *” 11 (2).

Link, Darren R, Erwan Grasland-Mongrain, Agnes Duri, Flavie Sarrazin, Zhengdong Cheng, Galder Cristobal, Manuel Marquez, and David a Weitz. 2006. “Electric Control of Droplets in Microfluidic Devices.” *Angewandte Chemie (International Ed. in English)* 45 (16) (April 10): 2556–60. doi:10.1002/anie.200503540. http://www.ncbi.nlm.nih.gov/pubmed/16544359.

Mills, A.F., Chang, B.H. 2004. “Error Analysis of Experiments: A Manual for Engineering Students.”

Pollack, M G, A D Shenderov, and R B Fair. 2002. “Electrowetting-Based Actuation of Droplets for Integrated Microfluidics.” *Lab on a Chip* 2 (2) (May): 96–101. doi:10.1039/b110474h. http://www.ncbi.nlm.nih.gov/pubmed/15100841.

Reichman, Jay. 2010. “Handbook of Optical Filters for Fluorescence Microscopy.”

Rosa, Albert J. 2005. “The Role Ofthe Laboratory in Undergraduate Engineering Education” (January).

Schmidt, Philip S, and Joseph J Beaman. 2003. “PROCEED : A Department-Wide Curriculum Reform Initiative in Project-Centered Education”: 1–12.

Sheble, E., S. Bickle, and C. H. Hidrovo. 2013. “Wind Energy Lab Module for Mechanical Engineering Undergraduate Curricula.” *International Journal of Engineering Education*.

Wilson, Michael, and Leslie E Gerber. 2008. “How Generational Theory Can Improve Teaching : Strategies for Working with the ‘ Millennials ’” 1 (1): 29–44.

Young, Edmond W.K., and Craig A. Simmons. “Integrating Low-Cost Microfluidics Into Undergraduate Teaching Labs to Study Multiphase Flow Phenomena in Small Vessels.”

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