Fluidic channels in the classroom: Fabrication and integration in fluid mechanics

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Fluidic Channels in the Classroom: Fabrication and Integration in Fluid Mechanics

Abstract: Micro-Electrical-Mechanical-Systems (MEMS) and Nanotechnology engineering education platforms based on thin film engineering have broad applications across all disciplines in science from semiconductor chip fabrication and accelerometers in unmanned aerial vehicles, to in-vivo medical instrumentation. Fabrication of real world thin film devices is an expensive, complex engineering effort that is not extensible to classroom laboratory environments. Having numerous cross disciplinary applications, fluid dynamics lends itself as a good model subject for laboratory demonstration of MEMS; flow visualization makes for an appealing demo, fluid flow scales to the nano regime, and fabrication of a UV epoxy microfluidic channel can be designed in a way that mimics standard MEMS fabrication techniques. UV epoxy has become a standard and relatively inexpensive material used in numerous optical applications and therefore is relatively inexpensive and readily available. Our fabrication technique follows the same general procedures used in MEMS: creation of a mask, photolithography, bonding, etching, and packaging. Fluidic channels are created between two glass slides in a thin layer of UV epoxy, the channels formed by flushing uncured epoxy with solvent. The microfluidic platform developed has been used in a chemical engineering fluid dynamics class for demonstrating various fluid dynamic phenomena, with a specific focus on frictional losses associated with various designs. In combining a fluid dynamic platform using MEMS fabrication techniques, a cross-disciplinary experimental engineering platform has been developed that can be further expanded into a teaching module including optics, surface chemistry, heat flow, as well as electrical phenomena.

Introduction

Many chemical engineering curricula (including the Chemical and Biological Engineering curriculum at Montana State University) focus on courses and developing a knowledge base prior to students enrolling in lab-based courses. The benefits of laboratory experiences are established [1-4], providing authentic examples of engineering tasks [5], thereby engaging learning further [6]. Active learning that occurs during the laboratory, rather than passive learning (such as lectures or reading) increases student engagement with a task or topic [6]. Collaborative learning, cooperative learning, and problem-based learning (PBL) are all considered as pedagogies of engagement [6,7,8] that can enhance student learning with proper implementation. The top two influencers on learning are interactions between students and interactions between faculty and students [7]; active learning, through cooperative learning and PBL, uses both influencers. Using a laboratory that the students engage with in the classroom may increase these interactions.

In Chemical and Biological Engineering (ChBE) at Montana State University (MSU), students have engineering laboratory experiences in their freshman year during the Fall semester and in the senior year during the Fall and Spring semester. The course focused on in this paper is ECHM 321, a three-hundred level Fluid Mechanics class typically taken by students at the sophomore level. Importantly, it does not have a formal laboratory component. Based on the aforementioned positive attributes of laboratories in the curriculum and successful implementation of demonstrations in the classroom [9], this project sought to bring simple microfluidics laboratory demonstrations into that class. Offered in both semesters of 2016-17, 47

students registered for Fall while the Spring offering had approximately 115 students. The course can be taken with Multivariable Calculus and Differential Equations as co-requisites, though most students have progressed to Differential Equations. The Material and Energy Balance course is a prerequisite. Montana State University is a land-grant university, and the Chemical and Biological Engineering department has over 600 undergraduate students.

To facilitate this laboratory experience in the classroom, the course instructor during the fall semester worked with the manager of the Montana Microfabrication Facility (MMF) on campus to coordinate efforts. The manager supervised a ChBE undergraduate over the summer and throughout the Fall term (Freshman into sophomore year) and a senior microfabrication lab technician in creating the microfluidic devices. The course instructor then used these on the last day of class during the scheduled "Final Exam Review Day" to ideally complement the traditional, paper-based review problems. This paper details the fabrication method to produce the microfluidic devices, implementation of the devices into the Fluid Mechanics course, results of a survey taken by the students on perceptions of this experience, and lessons for future iteration and adaptation into other courses.

Chip Fabrication Methods

A simple fabrication process of fluidics devices was used to bridge educational experimental science with student engineering interest. The method used the equipment noted in Table 1.

Table 1. List of equipment to design and fabricate inexpensive 'closed-face' microfluidic devices

1. UV lamp with collimation filter	2. BD Syringe and Needles
3. 47900 furnace (Up to 150 C degree capability range)	4. Scientific Commodities Tubing
5. Norland UV Epoxy adhesive: NOA83H, NOA63	6. UVA intensity meter
7. Corning glass slides	8. Black foam board
9. Spacer sheet - 1mm thick plastic sheets	10. Pictorico Premium OHP Transparency film
11. Binder clips	12. Pigment based Inkjet printer capable of printing at 2880 dpi
13. Developer - Acetone	

We created a microfluidic device from glass slides and a UV-sensitive adhesive by pouring a UV-curable epoxy between two glass slides separated by spacers [10,11]. By emulating standard microfabrication photolithography, the student developed an understanding of system engineering principles of Micro-Electro-Mechanical Systems (MEMS) in addition to course specific content. We mimicked photolithography processes by placing a printed transparency mask over the top of two slides with adhesive in between. The pigment based ink used in the inkjet printer blocks UV light (dark area) preventing exposure of the adhesive. With appropriate design of the photomask, we can pattern the fluidics channels with solvent, flushing the developable adhesive, leaving open channels in the epoxy layer. After inserting and curing needles into designed inlet channels, standard tubing can connect the needle to other flow equipment (in this case a column of water).

***Mask Design**:* Masks were designed in Microsoft Publisher. A black 2x3" box is first drawn to match the glass slide's geometry. All lines are colored black to minimize the amount of light passing through patterned areas. Using the various shape and line options, various channel

designs can be patterned on the mask. The conversion 1 mm = 2.83465 pt was used to select a line width in 'point' that could scale to the dimensions desired in mm. The masks can then be printed on a Pictorico transparency. With the equipment available, the paper type was set to premium photo paper glossy, quality set to max (2880 dpi x 1440 dpi), and the color set to advanced B&W Photo. Three versions of channels printed onto a transparency are shown in Figure 1a.

Pre-cure chip assembly: For demonstration purposes, the channels were larger than typical microfluidics and were on the order of 1 mm. One glass slide was first fitted with two 1 mm spacers on either edge to set the channel height. If channels enter/exit from all four faces, these spacers can be placed on the corners. The NOA83H UV adhesive was then poured onto the slide, filling up the area between the spacers. The second glass slide was then carefully placed on top by positioning one edge to the other to avoid air bubbles being trapped in between. This adhesive and two slides will be the final microfluidic device. The desired mask was then placed on top. To stabilize the mask and ensure flat contact, another glass slide was placed over the mask. From the bottom up, the system is now slide, adhesive, slide, mask, and slide (Figure 1b). Securing the device with binder clips in each corner further secures the device so it can be transported to the curing step. The pre-cured device with binder clips is shown in Figure 1c.

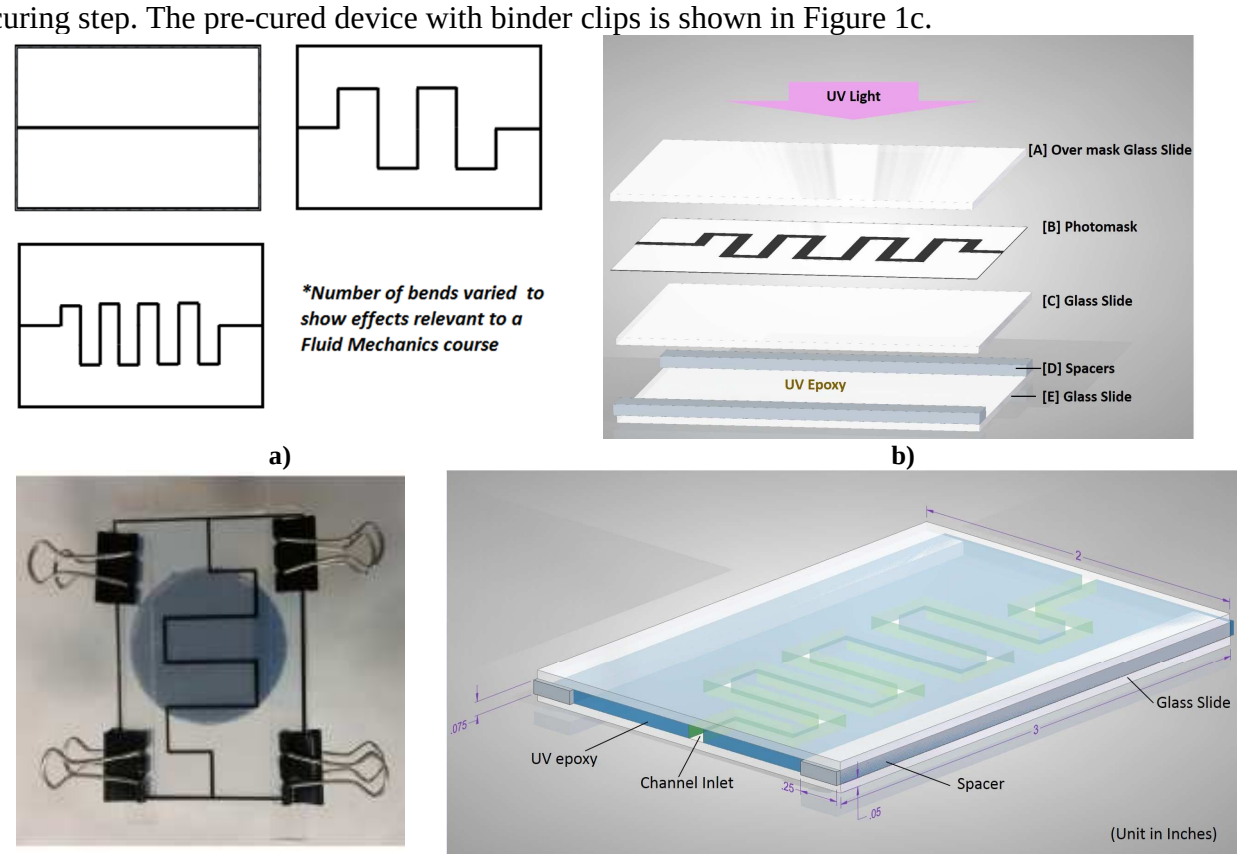
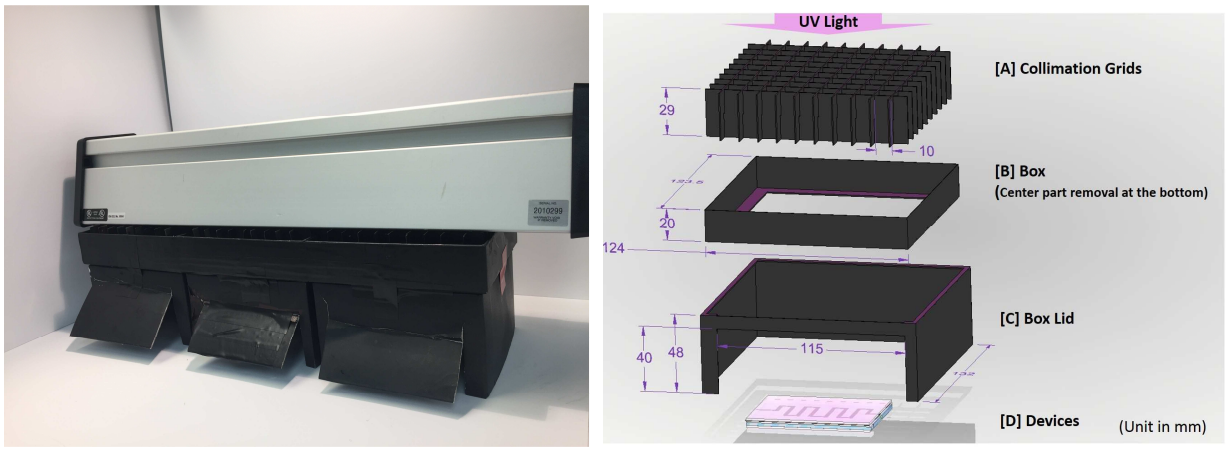


Figure 1 a) CAD drawings to print on transparencies, defining the geometry of the flow channel b) Exploded view of layers used to fabricate the device c) A device during fabrication held together via binder clips before UV curing d) Schematic of the components of a cured chip

UV light collimation: A Spectronics XX-15A bench mount UV lamp was used for UV exposure. This lamp emits UV light at 365 nm wavelength with rated intensity of 800 $\mu W/cm^2$ at

25 cm distance. To prevent exposing UV epoxy beneath the transparency patterns, some collimation of the UV light source was found to be necessary. We used a home-made collimator made of hard paper based bioreagents storage boxes. The collimation filter is 3.7 cm in height and consists of 1.2 cm by 1.2 cm grid units that block light >25 degrees from vertical (diagonal dimension) and greatly reduce light >18 degrees from vertical. This collimator was placed on top of a 7.5 cm tall spacer constructed to prevent operator exposure to the UV light. This enclosure was made with three openings for inserting UV fluid plates. These are highlighted in Figure 2. To prevent reflected light, we colored the white sample organizers with black paint. At a distance of 7.5 cm between the collimator and devices, ~11 cm from the UV lamp, the intensity is ~150 ±15 $\mu W/cm^2$.



a) **b)**

Figure 2 a) UV lamp and collimation system as set up in the lab b) Schematic of the collimation system to ensure even curing of the chips

Curing and flushing: Carefully move the device onto a piece of black foam board and cure for 3 minutes in UV light. Once exposed, a faint design resembling the mask should be apparent on the device. If the device is over-cured, a needle will not be easily inserted into any of the inlets or outlets and the channels will not be able to be flushed. If the device is under-cured, flushing acetone will remove more than the channel region. If the device is sufficiently cured, insert a needle into an inlet or outlet and carefully flush acetone through the device. Flush acetone through the device multiple times with a glass syringe and needle to ensure all uncured adhesive is fully removed.

Curing needles into the channels**:** In each inlet, a needle with the largest outer diameter possible was inserted into the channel. Additional uncured adhesive was placed at the interface of the needle where it meets the already cured adhesive. The chip was placed back onto the foam board and put back under the UV light to cure for another 3 minutes. Once the tip has been cured into the chip, it should not be easily removed by gentle pulling.

Hard bake: The chip is placed on a folded wiper and baked in the furnace for 10 minutes at 125°C. Remove from the furnace and allow the chip to cool.

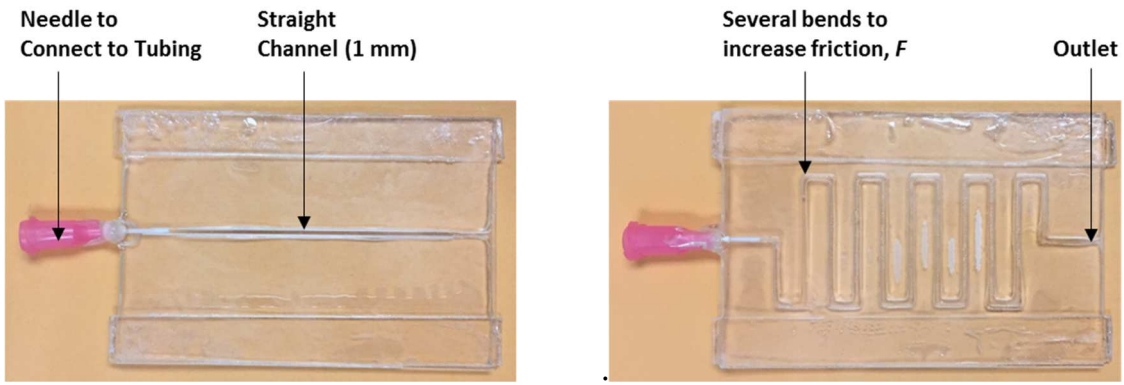
Characterization and testing: Fill a syringe with colored water and pump through the chip to characterize how the channels cured. Flow should only be visible in the channels and there

should be no leakage between the UV and the glass slide. The true channel thickness can be measured under the microscope.

Results and Discussion

This section focuses on the chips as fabricated for the Fluid Dynamics class, a final exam question based on the experiment, results of a survey taken by the students, and future improvements and implementation ideas.

***a) Chip design for the final exam review*:** On a 2”x3” glass slide, three specific chips were designed for use during an in-class final exam review day (the last day of class). The first chip was a straight channel with a channel width and depth of 1 mm. The second and third chips, also 1 mm in depth, contained 9 and 22 square 90° bends, respectively. The straight channel device and chip with 22 bends are shown in Figure 3.



a) **b)**

Figure 3. Two examples of constructed microfluidic devices with a) the baseline straight channel highlighting how the needle is inserted into the device and b) how different channel patterns can be formed to highlight different aspects of the demo (e.g. increasing F in Eqn. 1)

These channel patterns were chosen to vary the frictional dissipation term, *F*, of the General Mechanical Energy balance (Bernoulli’s Equation with Work and Friction).

$$\frac{P_1}{\rho} + \frac{u_1^2}{2} + gz_1 = \frac{P_2}{\rho} + \frac{u_2^2}{2} + gz_2 + W + F \qquad \text{Eqn. 1}$$

A schematic of the setup is shown in Figure 4. Flexible tubing was used to connect a conical funnel to a syringe. The conical funnel is advantageous because the slow draining system with a large cross sectional area means the height (i.e. driving force) does not change appreciably during the experiment and the velocity is nearly zero (kinetic energy term at Point 1 is zero). The syringe was needed as it provided a secure, leak-free connection to the needle that was embedded within the microfluidic device. Water was collected in a small beaker, and the weight of this system was subsequently measured. By weighing the dry beaker ahead of time, the weight of water was determined. By timing how long water collection occurs for, a mass flow rate was thus directly measured.

This experiment was utilized on the last day of class, which was a review day for the final exam. All students (n ~40 of 46) who came to class that day were first given a review packet with 20 questions covering all aspects of the course. The first fifteen minutes were dedicated to the first

three problems in the packet, which provided enough time for the students to be engaged with the review packet material. Then, over the remaining time, students in groups of approximately eight tried their own experiment for approximately 15 minutes. Although recommendations for group size in engineering PBL is ideally set at three, space, time, and equipment needs dictated we divided the student population into groups of approximately eight [7].

In each case, the instructor provided instructions to the group about the general setup including how to collect data. The subsequent experimental design was up to the students: height of water, whether to measure for a fixed time or fixed amount of water in the container, which of the three chips to use, etc.

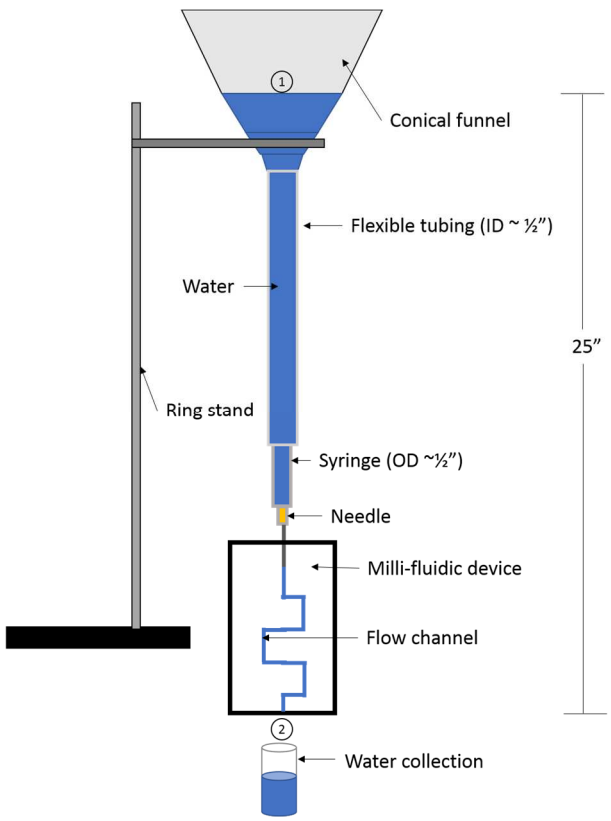


Figure 4. Schematic of the in-class experiment utilizing the microfluidic devices shown in Figure 1 and Figure 3**. The circled points '1' and '2' correspond to where terms are evaluated in the Mechanical Energy Balance (Eqn. 1).**

As part of the instructor's instructions, students were reminded that this was a physical representation of the mechanical energy balance (Eqn. 1 above). The instructor verbalized points '1' and '2' and how all of the terms were potentially in the system. For instance, the instructor was able to say "Look at Points 1 and 2; each is open to the atmosphere. This *is* the $P_1 = P_2 = P_{atm}$ approximation we have made in many written example problems." All students were encouraged by the instructor to try to connect the dots between various *draining tank* problems solved in homework and in-class problems and the system in front of them.

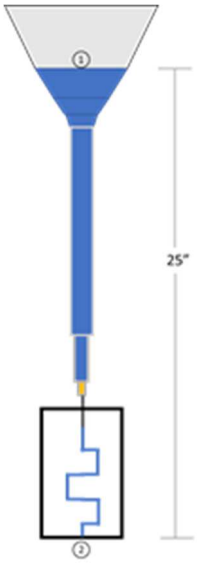
***b) Final exam question based on in-class laboratory*:** The final exam was eight days after the review session. It was comprehensive in that it covered topics throughout the course. Considering the broad applicability of the experiment done during the review day, one exam question worth 5% of the final exam score was included (final exam was 20% of the course grade). This question addressed not only the experiment from the review day but also a clear student *misunderstanding* that the instructor observed earlier in the semester. Of the five terms in Equation 1 (Mechanical Energy Balance), the importance and/or magnitude of the kinetic energy term ($u^2/2$) can be unclear. Even in some homework problems from the course textbook, students are told "Ignore exit kinetic energy effects" without further explanation. In other cases, an argument is made via mass conservation for an incompressible fluid, where $u_1A_1 = u_2A_2$, that if one area is much bigger than the other, the velocity at that point would be correspondingly small, leading to negligible kinetic energy. The instructor's experience is that students tend to see that those terms *go away* but do not develop a deeper understanding on *why*. Considering this was a point of emphasis in the review packet and

related to this experiment, it seemed a fair question on the final exam to gauge if the students had more comprehension of why certain terms in the balance were removed.

The question was:

"Recall the experiment you all did on the last day of class. The height of water in the column is 25" and you measure a flow rate of 0.000213 kg/s. I used the mechanical energy balance and simplified it to $gz_1 = F_{total}$*. This means* F_{total} *= 6.23 J/kg.*

- *The cross sectional area at the top of the column of water (Point 1) is 0.00456* m^2 *and the cross sectional area in the microfluidic channel's exit (Point 2) is* $1x10^{-6}$ m^2*.*
  a. *[3 pts] Calculate the kinetic energy terms [*$\frac{u_1^2}{2}$ *and* $\frac{u_2^2}{2}$*].*
  b. *[2 pts] Is my assumption to ignore these terms reasonable?"*



Of the 46 students registered to take the Final Exam, the average score on the exam was 78% (two students did not attend; 82% excluding them). In this course, a grade less than 70% is not passing. In terms of the above question related to the microfluidic module, 16 students of 44 (36%) got both parts entirely correct. Part A was a comparatively simple question even without the review-day laboratory considering the information given in the question's text. Incorrect answers to this part and the number of instances include: wrong or missing units (4), no work (6), the wrong approach overall (8), and a calculation error (7). The students with no work and the wrong approach overall are 32% of the students. Part B involved more analysis, and it appears the students did reasonably well. Incorrect answers to this part and the number of instances include: an inconsistent interpretation of the results in Part A (3), an argument based on mass balance/a relatively small velocity as opposed to small kinetic energy terms (6), no work (7), and the wrong direction overall (2). The majority of the students were able to make the correct assessment in Part B that the results in Part A were negligibly small compared to the remaining relevant terms in the Energy Balance. Considering where most students seemed before the review and the final exam, it appears the review packet certainly helped, and the experiment may also have played a part.

c) Survey results: To gauge the effectiveness of the experiment during the final exam review, the students were sent a survey at the beginning of the Spring semester (after the course had ended). As this was the first such attempt to integrate this laboratory into the course, the questions focused on perceptions of effectiveness in helping learning and how the experiment in class could be made better. These questions are listed in Table 2. The first fifteen questions were on a 5-point Likert scale from Strongly Disagree to Strongly Agree with Neutral in the center. The survey was optional and anonymous. It was administered through Qualtrics, and a link was sent to the students. Prefacing the survey was the text: "The following questions relate to the 'microfluidic experiment' you did in groups during the Final Exam Review. There are 15 multiple

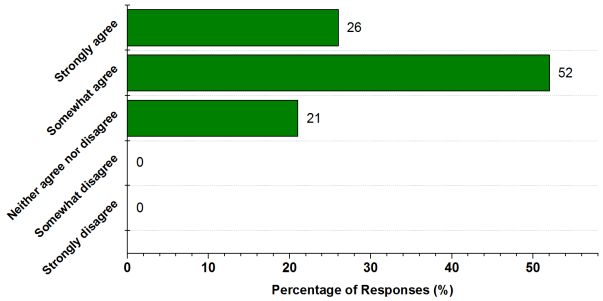
choice questions and a few open-ended response areas. As a reminder, you attached various microfluidic devices with different channel designs to a column of water. You could fill that column with water to a height of your choosing and use a stopwatch and scale to determine information on the mass flow rate."

Table 2. Survey sent to the students in the first month of the following semester, including fifteen questions on a five-point Likert scale and four open-response questions

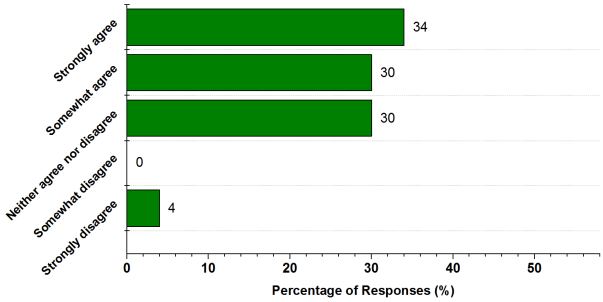
Questions (1-5)	**Questions (6-10)**	**Question (11-15)**
1. The demonstration helped me learn core content related to Fluid Mechanics	6. More small labs/demonstrations during the course would be helpful to my learning	11. I learn more by doing 'hands on' activities
2. I enjoyed working in a group	7. The demonstration helped me prepare for the final exam	12. I would recommend doing this demonstration in future ECHM 321 courses (such as during lecture or on review days)
3. I liked designing the experiment as a group	8. The review packet was complemented by the demonstration	13. This demonstration would be more valuable right when we learned about the Mechanical Energy Balance
4. I better understood the Mechanical Energy Balance because of this demonstration	9. The open-ended nature of the demonstration made me more confused	14. This single demonstration should be used multiple times throughout the course to highlight different topics
5. The demonstration detracted from the overall "Final Exam Review" day	10. I would prefer someone leading the demonstration while I watched	15. I would use a "maker-space" area dedicated to designing my own "fluid dynamics" experiments
Open Ended Question		
16. Did this demonstration help you prepare for the final exam? If so, how? If not, why not?		
17. How effective was your group at collaborating? Explain. (Or, how would you describe your group's collaboration?)		
18. Given the opportunity to do this again, what would you change?		
19. Additional comments:		

In total, 23 students responded out of 46 (50%). Overall, the student response was positive. Results from eight of the fifteen Likert based questions are shown in Figure 5. The students in general think they learned more core content of the class and better understood the mechanical energy balance because of that experiment. However, students were mixed on whether it detracted from the final exam review day and mostly did not agree that it better prepared them for the final exam. In addition, a majority agreed that more small labs/demonstrations throughout the course would help learning and that this experiment should be done in the future in this course.

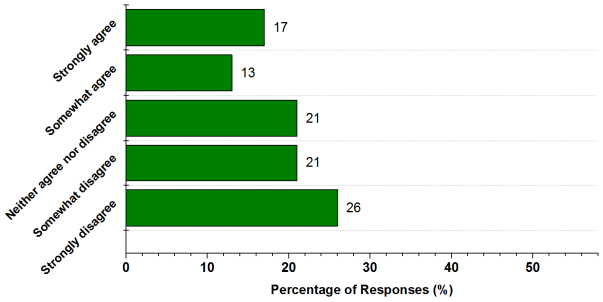
Q1 - The demonstration helped me learn core content related to Fluid Mechanics:



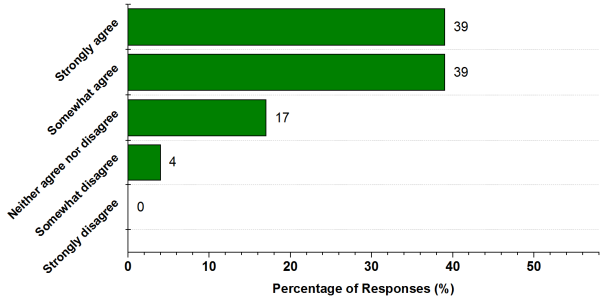
Q4 - I better understood the Mechanical Energy Balance because of this demonstration:



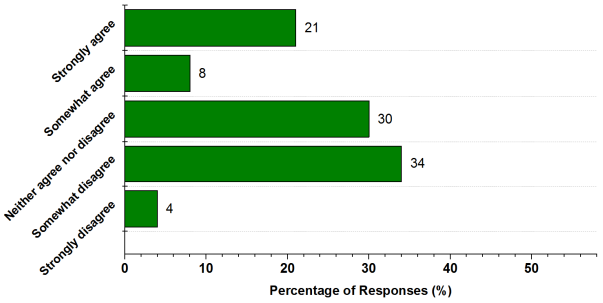
Q5 - The demonstration detracted from the overall "Final Exam Review" day:



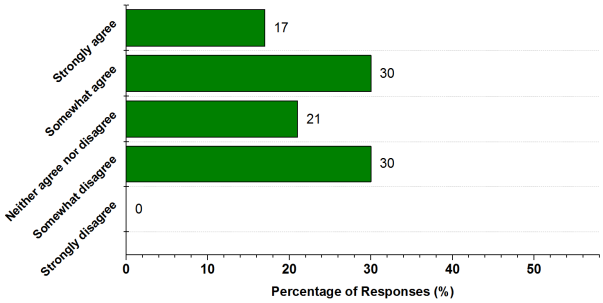
Q6 - More small labs/demonstrations during the course would be helpful to my learning:



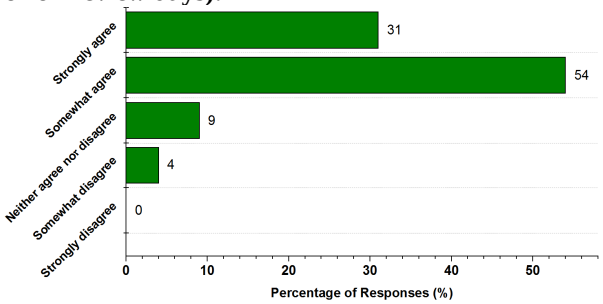
Q7 - The demonstration helped me prepare for the final exam:



Q10 - I would prefer someone leading the demonstration while I watched:



Q12 - I would recommend doing this demonstration in future ECHM 321 courses (such as during lecture or on review days):



Q15 - I would use a "maker-space" area dedicated to designing my own "fluid dynamics" experiments:

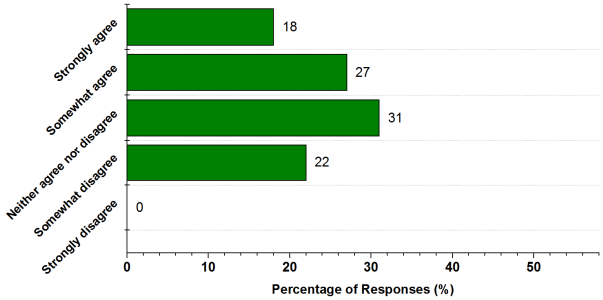


Figure 5. Select responses to the five-point Likert scale questions from Table 2

The students also provided feedback to the open-ended questions. Select responses are shown here along with a more summative assessment based on the instructor's interpretation of the comments.

Q-16. Did this demonstration help you prepare for the final exam? If so, how? If not, why not?

Not really only because I was already confident in my the final especially with mechanical energy portion, but it did not detract from the review.
I had trouble making the connection from a mass flow rate to a mass balance in time for the experiment to give me a better understanding of the mechanical energy balance.
No, it took a lot of time and our groups were too big. "too many cooks in the kitchen" type of thing.
It didn't help me prep for the exam necessarily, but it did help solidify the mechanical energy balance equation we learned in class.
I feel like it was somewhat on a different way of thinking of things so I am pretty neutral about if it helped for the exam
I did not help me prepare much because it was such a basic concept. But it did help remind me of older information.
Not exactly because I already had a good comprehension of what was going on in the mechanical energy balance.
Not really, I think it is a good idea
No, throughout the course we learn about fluid dynamics through equations and solving problems on pen and paper. I became more comfortable studying for the final exam by reworking homework problems and related problems in class, and not by visualizing the demonstration. Although the demonstration is a powerful way to observe and study fluid dynamics, demonstrations as a method of learning in general was not a primary focus throughout the course (although I appreciated them and learned from them).
I understood the topics before the demonstration, it neither helped nor hurt my preparations.
It helped tie together nebulous concepts so that I had a better understanding of energy balances and effective length
I knew the Mechanical Energy Balance before the example, but this example really helped translate from conceptual to real.

The overall impression seemed to be that most of the students who answered this question already had a reasonable grasp of the topic, and as such the laboratory did not greatly aid in preparation for the test. However, as noted by several students in Q.18, had this experiment been attempted on a day different than one perceived as having higher stakes (final exam review day), the response would likely have been more varied.

Q-17. How effective was your group at collaborating? Explain. (Or, how would you describe your group's collaboration?)

We were the last group who was kind of rushed so it was just okay, but we all helped on the process.
It seemed we were all pretty lost, because nobody was very clear on why we were trying to record a mass flow rate, that is what we were trying to find out.
Not very, and we didn't get enough time to really figure things out.
It was a good experience to let the groups figure it out themselves. It took us a couple of times to get it right, but once we did it made sense.
We collaborated pretty well there was simply difficulty in settling on a track for the project with how open it was
My group was effective but we didn't know each other so the experiment was as successful.
We were fairly good at it, we only had small arguments
Not to effective we needed better leadership so I stepped up. It ended working out in the end and we got some measurements.
My group's collaboration was poor, as we felt a time constraint in getting the experiment recorded and saving enough time to focus on the other exam review questions. We did not have a good method of controlling the stop/start of water flow (leaking was an issue) and stopwatch measurements.
My group was not very effective. I think that this was largely because of the limited time.
The group kinda made three people the "heads" and then chimed in with ideas when they couldn't reach consensus. It worked relatively well.

The most common response spoke to dysfunction in the large-group setting. Students had to quickly interact and, in some cases, may have not known each other (as can happen in a class with 46). There may also have been a tendency to remain quiet as to not say something "wrong" in front of the group. It is encouraging that some students felt comfortable stepping into a leadership position. Research on cooperative learning and PBL indicates that neither happen serendipitously when students are thrown together; students need to be taught *how* to work in cooperative groups, must have smaller group sizes, particularly in engineering (3 is considered optimal), and need to be given a clearly structured problem with some idea of what the task requires them to do [7].

d) Future improvements and integration into other courses in the college of engineering: The open-ended comments here provide useful feedback for the instructor.

Q-18. Given the opportunity to do this again, what would you change?
I would definitely do it around the time we first learned mechanical energy balances.
The group size and when we did it in relation to the course.
I would do this experiment on a day other than the review. It would help to do it when we learned about that kind of problem. It didn't necessarily distract from the review session, but I think the review would be more effective/(make everyone feel more prepared) if it were a solid class day of going through examples and talking them through.
Be quicker to just pick a subject and get deeper into it
I would do it again but I would do it right after we learned about the mechanical energy balance.
I would like more time to do it
A little bit more clarity on the directions of the experiment. Smaller groups. More people focused on calculations.
It would interesting to try to split the class into two or three sections, with each section containing a group to do the experiment. Each of the two/three (large) groups would fill out a multiple question worksheet on their calculations after performing the experiment. The worksheet would encompass everything from hydrostatics (with the column of water), to the mechanical energy balance and solving for Reynolds numbers, friction factors, and outlet conditions. So on the final review day, students would spend about 1/3 of the class performing the experiment, 1/3 completing the worksheet, and 1/3 completing other final exam review problems.
I would put it earlier in the semester and provide more time for each group to do their trials.
Either larger groups or more burettes, since my group ran out of time.
Put some dye into the fluid so it is easier to track through the channels.

Despite the fact that most students did not see this approach as beneficial to the review, they did see it as beneficial overall and offered suggestions to improve the approach. Without any knowledge of pedagogical strategy, student reflections on their experiences pinpointed what needed to be adjusted including the use of smaller groups, clearer task instructions for the problem, and more structuring of both the grouping and the task—all elements of effective PBL and cooperative learning practices. The ultimate timing of the device fabrication led to some practical restrictions on classroom implementation during the review day, and given the opportunity, we would have chosen a different date. Implications for others who might utilize this approach are to take note of the student suggestions and do the following: (1) structure the PBL experience and provide cooperative learning guidelines, (2) do this on more than one occasion so students have more preparation in working these approaches; (3) make the goal of the activity and the instructors' role clear to the students; and (4) have students assess the experience and thus influence future iterations.

Based on this feedback and the responses in Q.16 and Q.17, the instructor plans on implementing two key changes. First, a brief written overview on the experiment will be provided to the students in advance of a review session near Exam 1, closer to when this content is covered first in the classroom. As opposed to describing how to do the experiment or listing experimental outcomes, it will outline what is included experimentally and how the students should think about what experiments could be run in relation to the Mechanical Energy Balance. This time to ponder prior to the review session should allow the students to have more productive discussions before deciding on what experiment to run. Second, more stations must be added so that groups can be (a) smaller and (b) have more time. Smaller groups mean that students will have more chances to participate directly. Having the handout done ahead of time means less explaining initially to these groups, allowing more focus on their proposed experiments and questions they have *during* the experiment as opposed to *before* the experiment.

Prior efforts using UV epoxy based micro/milli fluidics have shown great promise as an engineering educational platform [12]. Working with the manager of the microfabrication facility in the College of Engineering, future work will focus on new chips that can be integrated in this and other courses. The in-classroom implementation described here can serve as a basis for other instructors to design their own modules. In the class described here, extensions can be made to biological applications such as gas-liquid flows related to embolisms [13]. Beyond this classroom, two focus areas are in (1) Reactor Design, a junior level course in Chemical and Biological Engineering and (2) optical detection of fluid flow and fluid reaction phenomena. An additional engineering platform within optics to explore is light guiding, which can be used in optics and physics classes. This will allow demonstration of optical properties and phenomena such as polarization, wavelength dependence, Brewster's angle, etc. Additional long-term studies could include ferrofluids or electrokinetics in conjunction with UV channel plates, which broaden the applications that can be demonstrated. Further cost reduction should be possible by incorporation of 3D printing UV materials in place of UV epoxy.

Conclusion

This work demonstrated how incorporating an active learning laboratory experience into a lecture-based course—in this case a student microfluidic based experimental module—appears to be a useful innovation that can be used to increase student engagement and possibly student learning (with further modifications). The UV fabrication procedure is low cost and flexible, allowing for a transferable platform to courses that do not typically have a laboratory component associated with them. Specific to this situation, three microfluidic devices were used during the Final Exam Review Day of a Fluid Mechanics class in the Chemical and Biological Engineering Department at Montana State University. Successful fabrication of relatively inexpensive devices by the Montana Microfabrication Facility allows this type of demonstration unit to be implemented in smaller groups as noted in referenced studies. Based on our experience developing these channels for Fluid Mechanics, the primary challenge for implementing these UV flow channels into in-class demonstrations is maintaining simplicity in the setup and device fabrication so the underlying engineering and scientific principles are not clouded by the complexity of the demonstration. Future iterations will continue to refine the implementation in the Fluids course, including more structure based on best practices in PBL. These approaches, coupled with the ability to craft custom microfluidic chips, will allow this approach to be adapted to other courses in the department and to other institutions. Integration of optical sensors,

mechanical actuators, electrical sensors, and actuators to this core platform allows extension of this lab fabrication platform into any engineering/science course.

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