AC 2012-3059: INTRODUCTION OF "MICROFLUIDICS" TO UNDERGRADUATE FLUID MECHANICS COURSES

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Abstract

Undergraduate level fluid mechanics course is traditionally taught as a math-intensive course with the content remaining fairly similar for decades. The course content is usually challenging for students with significant amount of theory and numerous new concepts introduced. In a fluid mechanics course, only a limited amount of state-of-the-art technologies and real-life applications can be included, given the limited time and the material that should be covered. Information on market and career opportunities are often not mentioned in fluid mechanics and other similar courses, which might also be very helpful for undergraduate students. In this paper, we present our efforts and outcomes of introducing the microfluidics module to the undergraduate fluid mechanics course - Fluid Systems - in the Mechanical Engineering Department at University of South Florida, Tampa, FL. Our main aim was to introduce the microfluidics world, give the students an insight to state-of-the-art fluid mechanics applications and micro-technology, and show them the concepts they were taught in the class are applicable to start-of-the-art applications, which could possibly lead to further interest in fluid mechanics.

Microfluidics, as the name implies, is the science of fluid mechanics in the micro scale. Microscale fluid systems are composed of several micro-components capable of processing and precisely manipulating very small volumes (pico-liter to micro-liter range) of fluids. It is an interdisciplinary field involving engineering, bioscience, chemistry, micro-technology and life sciences. The microfluidics module was based on one and half hour-long lecture piggybacked with illustrations and videos. The concept of microfluidics and related theory; its advantages, related challenges; cutting edge applications; market information and career opportunities on microfluidics were introduced. Additionally, an acoustic microfluidic device for particle separation and mixing developed by our research group was also demonstrated and discussed in detail. The evaluation of the module for content, effectiveness and impact was done with the help of a survey composed of nineteen multiple choice questions, student comments and face-to-face discussions. It was observed from students’ responses and the survey that the module has drawn significant interest on fluid mechanics and microfluidics. It also inspired a significant number of students to work or conduct research on microfluidics and related areas. The students, in general, were more than happy to see how the concepts they were taught in the class are applicable to microfluidics.

Introduction

Fluid mechanics is a junior level required course in mechanical engineering curriculum. Some of the mechanical engineering programs around the country offer the course as a two semester long course. In a typical one semester course the topics covered are: introduction to fluid mechanics and properties of fluids; fluid statics; fluid kinematics; control-volume analysis; differential analysis of fluid flow; similitude; internal flow and external flow. The topics covered in a two
semester fluid mechanics course in addition to the ones listed above are: compressible flow, pipe flow and turbo-machinery. Fluid mechanics courses are generally math intensive, which include significant amount of theory.

Our previous end of semester surveys usually illustrate that there is a lack of hands on experience and information on applications in thermo-fluid science courses. Even with the experiments performed during the semester, the majority of the course content is reserved for the massive amount of topics, concepts and theory. Furthermore, the extensive theory cannot be easily applied to real world applications. Fluid flow is a complex phenomenon that usually requires models far more complex than the undergraduate level understanding and numerical methods are frequently employed for actual applications. Computation fluid dynamics (CFD) is essential but, far more advanced for undergraduate level also. Even tough, there are efforts to introduce CFD to undergraduate curriculum, it is still hard for students to work on a problem on their own and come up with solutions to real life applications. It is beneficial for students to learn how to apply and use CFD, but the efforts usually cannot proceed further than teaching students how to use the software packages. There are also other efforts for better understanding of fluids applications such as hands-on experiments as an alternative to full scale experiments. As a conclusion, special care should be given to introduce applications to students and provide them with hands on experience for fluid mechanics courses. This would enhance students’ interest on the topic and will lead to a better learning experience.

In this study, we have developed a lecture on microfluidics, one of the hot topics in fluid mechanics, and introduced the world of applications of microfluidics to undergraduate students. Microfluidics has a wide application domain ranging from inkjet printing to lab-on-a-chip devices for medical diagnosis. We aimed to introduce this very important and interesting branch of fluid mechanics to compensate for the lack of applications taught in the course and to draw interest on fluid mechanics in general. The lecture was based on one and half hour-long presentation involving an introduction, theory, design, applications, market and job information. The presentation was supported with numerous illustrations, pictures and videos.

The evaluation of the lecture and its outcomes were measured with a survey handed out to students at the end of the lecture. The survey was composed of 19 multiple choice questions under three headings: content, impact and future directions and a section to which students write their comments on. The content of the lecture will be listed in the next section, followed by the method and results of survey including student comments. In the last section, the effectiveness and outcomes of the lecture will be discussed based on the results followed by planned future work.
Lecture Content

The microfluidics lecture was based on a presentation with 60 PowerPoint slides including introduction to microfluidics and scaling laws, basic theory, design methods, state-of-the-art applications, current and projected market and career opportunities. The content covered under each heading listed is described below. The main emphasis was on introducing students the state-of-the-art technology of microfluidics and its applications. The lecture was taught towards the end of the semester. The lecture materials including the presentation are available for download in the webpage: http://me.eng.usf.edu/Faculty/guldiken/TUTORIALS.html.

Introduction and Scaling

The introduction part started with the definitions, stating the need for microfluidics and typical components in a microfluidic system. The advantages (also disadvantages) of microfluidics were discussed in detail, mainly resulting from the scaling down from macro scale to micro scale. The dimension and volume scale were presented with illustrations (Figure 1) enabling students better visualization of the scales. The advantages and disadvantages on sample size requirements, process and analysis times, sensing techniques, handling, portability and the effects of viscosity, inertia, flow regime and capillary forces were described in detail with the effect of scaling down. Following the scaling and advantages, the application space and sciences related with microfluidics were mentioned. A brief history of microfluidics was also included starting from the very first ideas on the topic that emerged in mid 70ies to first commercial products in the late 90ies.

Figure 1. Visual material for introducing dimensional and volumetric scaling
Theory and Validity of Continuum Hypothesis

Considering junior and senior level students have limited knowledge and understanding on flow and transport equations, the theory of microfluidics was discussed briefly. Validity of continuum hypothesis was discussed by defining Knudsen number, upon which macro-fluidics are built. The validity of continuum hypothesis for micro and nanofluidic systems were described and types of flow regimes in various microfluidic components were introduced. The flow features affected by viscous, capillary and diffusion characteristics in micro-flow were also mentioned using the related non-dimensional numbers.

CFD in Microfluidics

As stated in introduction, computational fluid dynamics (CFD) is frequently used in designing microfluidics, because of the complexity of the phenomena and various mechanisms involved. The use and importance of CFD in microfluidics design and optimization were illustrated using examples and graphs from the available literature. The effects of component sizes, type of liquids involved and environmental conditions on performance was demonstrated and it was shown that computer aided optimization is necessary. CFD basics and its applications in microfluidics were introduced without going into too much detail, but detailed enough to show students the importance and use of it.

Applications

A significant portion of the lecture (around 25 slides) was devoted to introducing state-of-the-art applications, explaining their significance and importance. Several lab-on-a-chip devices were demonstrated such as commercial products such as Caliper’s Lab Chip® and DNA, RNA and protein analysis platforms (Handylab®, IntengX®), a microfluidic system that can be used with conventional CD players along with a non-commercial applications such as medical diagnosis and general use microfluidics platform (SmartHEALTH), systems for oral drug delivery and particle separation and mixing. Also another interesting application of a remote controlled lab-on-a-robot device for explosive detection, was introduced. Lab-on-a-chip technology and devices were the main emphasis due to them being the most promising and interesting application utilizing microfluidics. The surveys identified that the student found the application section as the most interesting part of the lecture, which inspired a lot of them.

A microfluidic device for particle separation, focusing and mixing developed by our research group was also presented in detail (Figure 2). The device is composed of an open loop microchannel fabricated in PDMS and micro-fabricated interdigital transducers (IDT) on piezoelectric substrates utilizing surface acoustic waves. Particle focusing, separation and mixing is performed by altering the design and using ultrasonic standing wave patterns. Separation with
respect to particle size or density can be achieved, which has potential use in lab-on-a-chip systems, especially in diagnostics. Separation, mixing and focusing of particles, cells and proteins are essential for effective sensing systems and is used to amplify the target particles from samples\textsuperscript{6}. The device operation requires a bulk and expensive setup composed of an external micropump and a fluorescence microscope, which was not feasible for demonstration in a large lecture hall far away from the laboratory. The videos captured during device operation were shown instead, along with an illustration and pictures of the device, which probably drew the most attention among other applications.

*Market information and Career Opportunities*

The market information and career opportunities were then discussed, especially for the students who might be further interested in microfluidics after the lecture. Current market information and predictions on the future of microfluidics and biomedical sciences market were mentioned. The companies working on microfluidics and related fields were listed for reference to students. Critical market segments were also shown and an overview on the business models for the microfluidics technology was listed.

The lecture ended with an overview and the discussion on challenges in microfluidics with the current state-of-the-art. The survey was then conducted at the end of the lecture after question and answer session.

![Figure 2. Novel microfluidic particle separation and mixing device developed](image)

**Evaluation**

The evaluation of the lecture was done with the help of a survey and student comments. It was first planned to have two surveys, before and after the lecture. When the lecture was firstly mentioned in class, it was seen that only a few students had heard about microfluidics so it was decided to hand only one survey at the end. The survey was composed of 19 multiple choice
questions under three headings: content, impact and future directions and a section for students to write down their comments. The choices for each question were: “strongly disagree”, “disagree”, “neutral”, “agree” and “strongly agree”. The evaluation was further expanded with the comments section of the survey and by face-to-face discussions.

The multiple choice questions asked in the survey are listed below:

- **Content of lecture**
  1. The microfluidics lecture was useful.
  2. The content of the lecture was adequate.
  3. The organization of the lecture was good.
  4. The duration of the lecture was adequate.
  5. The theory of microfluidics in the lecture was adequate.
  6. The microfluidic applications presented in the lecture was adequate.
  7. The market and job information about microfluidics was adequate.
  8. After the lecture, I understand the advantages and disadvantages of microfluidics over microfluidics.
  9. The videos and illustrations shown were adequate.

- **Impact**
  10. Before the lecture, I had interest in fluid mechanics/microfluidics.
  11. After the lecture, I have more interest in fluid mechanics/microfluidics.
  12. The market and opportunities in microfluidics and its biological applications will expand in the future.
  13. Before the lecture, I would like to pursue research/ work on microfluidics.
  14. After the lecture, I would like to pursue research/ work on microfluidics.

- **Future Directions for the Course & Curriculum**
  15. Demonstration of the applications in the Fluid Systems course other than this microfluidics lecture was adequate.
  16. I would prefer to have another lab on/ substitute one of the labs for the Fluid Systems course with a microfluidics lab.
  17. I would like to have some hands on experience on microfluidics in this course.
  18. I’m interested in seeing live demonstrations of microfluidic devices/experiments.
  19. I would like to have more similar application-based courses or lectures in other courses in the mechanical engineering curriculum.

63 students attended the microfluidics lecture, out of 80 students who were officially registered for the course. All of them filled up the multiple choice survey. Out of 63, 35 (55.5%) of the students also wrote down their personal comments. The result of multiple choice surveys is given in Table 1 below.
Table 1. Results of the Survey

<table>
<thead>
<tr>
<th>Content of lecture</th>
<th>Strongly Disagree</th>
<th>Disagree</th>
<th>Neutral</th>
<th>Agree</th>
<th>Strongly Agree</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) The microfluidics lecture was useful.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>14</td>
<td>32</td>
</tr>
<tr>
<td>2) The content of the lecture was adequate.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>10</td>
<td>32</td>
</tr>
<tr>
<td>3) The organization of the lecture was good.</td>
<td>0</td>
<td>2</td>
<td>3.2%</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>4) The duration of the lecture was adequate.</td>
<td>0</td>
<td>8</td>
<td>12.7%</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>5) The microfluidic applications presented in the lecture was adequate.</td>
<td>0</td>
<td>2</td>
<td>3.2%</td>
<td>5</td>
<td>28</td>
</tr>
<tr>
<td>6) The theory of microfluidics presented in the lecture was adequate.</td>
<td>0</td>
<td>1</td>
<td>1.6%</td>
<td>15</td>
<td>21</td>
</tr>
<tr>
<td>7) The market and job information about microfluidics was adequate.</td>
<td>1</td>
<td>0</td>
<td>0%</td>
<td>12</td>
<td>23</td>
</tr>
<tr>
<td>8) I understand the advantages and disadvantages of microfluidics over macrofluidics.</td>
<td>2</td>
<td>3.2%</td>
<td>4.8%</td>
<td>15</td>
<td>28</td>
</tr>
<tr>
<td>9) The videos and illustrations shown were adequate.</td>
<td>0</td>
<td>4</td>
<td>6.3%</td>
<td>9</td>
<td>30</td>
</tr>
<tr>
<td>Impact</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>10) Before the lecture, I had interest in fluid mechanics/ microfluidics.</td>
<td>4</td>
<td>6.3%</td>
<td>12</td>
<td>19.0%</td>
<td>19</td>
</tr>
<tr>
<td>11) After the lecture, I have more interest in fluid mechanics/ microfluidics.</td>
<td>0</td>
<td>0.0%</td>
<td>4</td>
<td>6.3%</td>
<td>10</td>
</tr>
<tr>
<td>12) The market and opportunities in microfluidics and its biological applications will expand in the future.</td>
<td>0</td>
<td>0.0%</td>
<td>0</td>
<td>0%</td>
<td>7</td>
</tr>
<tr>
<td>13) Before the lecture, I would like to pursue research/ work on microfluidics.</td>
<td>4</td>
<td>6.3%</td>
<td>19</td>
<td>30.2%</td>
<td>26</td>
</tr>
<tr>
<td>14) After the lecture, I would like to pursue research/ work on microfluidics.</td>
<td>1</td>
<td>1.6%</td>
<td>4</td>
<td>6.3%</td>
<td>27</td>
</tr>
<tr>
<td>Future Directions for the Course &amp; Curriculum</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15) Demonstration of the applications in the Fluid Systems course other than this microfluidics lecture was adequate.</td>
<td>0</td>
<td>0.0%</td>
<td>3</td>
<td>4.8%</td>
<td>17</td>
</tr>
<tr>
<td>16) I would prefer to have another lab on/ substitute one of the labs for the Fluid Systems course with a microfluidics lab.</td>
<td>1</td>
<td>1.6%</td>
<td>4</td>
<td>6.3%</td>
<td>12</td>
</tr>
<tr>
<td>17) I would like to have some hands on experience on microfluidics in this course.</td>
<td>1</td>
<td>1.6%</td>
<td>2</td>
<td>3.2%</td>
<td>5</td>
</tr>
<tr>
<td>18) I am interested in seeing live demonstrations of microfluidic devices/experiments.</td>
<td>0</td>
<td>0.0%</td>
<td>0</td>
<td>0.0%</td>
<td>4</td>
</tr>
<tr>
<td>19) I would like to have more similar application-based courses or lectures in other courses in the mechanical engineering curriculum.</td>
<td>0</td>
<td>0.0%</td>
<td>1</td>
<td>1.6%</td>
<td>6</td>
</tr>
</tbody>
</table>
Assessing these results, for the first nine questions asked for the course content, in average 80% of the students found the course content adequate and useful. It is very fortunate that none of the students found the lecture and content to be not useful. The lecture itself, its content, its organization, presented applications, theory, market and job information and illustrations were all anticipated as “good” and “adequate”, by more than 80% in average. Students found the duration of the lecture a little short. It is anticipated from the students’ comments that, they felt that the lecture should be longer than it was, considering the amount of material presented. Some also related this to covering the topics in detail more than it should. Some comments received from the students about the duration were:

“*A little less theory and more applications in the microfluidics lecture would be helpful. The amount of theory was hard to follow in such a short time*”

“All in all good presentation, but too much information in a too short time.”

“The presentation would be better. If it was not rushes and was more of just an overview.”

Even though only 8 students (12.7%) disagreed with duration was enough and over 60% of students find it adequate. However, we are planning to arrange a longer lecture for next semesters. We will also reconsider the detail level of each topic. The slides on differences between micro and macro fluidics will be revised, based on the feedback from the question 8.

The market and job information was also found to be very helpful, most probably because similar topics are not frequently mentioned in engineering courses in general. Showing them the job opportunities really drew interest. Some comments supporting this argument were:

“It definitely helped me understand the possibilities there are in the field and potential growth in the future, which is a very important face when decided on my career.”

“Very well organized, lots of info. Good use of profit/money info to promote interest.”

The results obtained from the questions under the “Impact” heading clearly show that the lecture reached its goal. The students that answered to have interest (who marked “agree” and “strongly agree”) in fluid mechanics and microfluidics have increased from 44% (n:28) to 78% (n:49) resulting in 75% increase. Furthermore, the students who are planning to have a career on fluid mechanics and microfluidics have increased from 22% (n:14) to 49% (n:31) resulting in a 121% increase in a similar manner. The distribution of the answers regarding interest in fluid mechanics and microfluidics (questions 10 and 11) and career on this field (questions 13 and 14) are illustrated in Figures 3 and 4. The results obtained from first part are further supported by the majority of the comments as:
“... Definitely inspired me to continue my education with this lecture.”

“Enjoyed the lecture and I am really interested in learning more/possibly getting involved with microfluidics.”

“The presentation was very informative. I will be looking for more information about this topic in the future.”

“I enjoyed learning about the applications of studying microfluidics. It seems very applicable to many areas in health. I would like to learn more about this subject area.”

Figure 4. Students’ response to questions 13 and 14, percentage of students planning to have a career on fluid mechanics/microfluidics before and after the lecture

Figure 3. Students’ response to questions 10 and 11, percentage of students who had interest in fluid mechanics and microfluidics before and after the lecture
The last part of the evaluation survey was the questions on future directions for the Fluid Systems course, microfluidics and mechanical engineering curriculum. Even if most of the students agreed that the amount of applications mentioned during the course was adequate, we are planning to work on further improving it for the following semesters. The comments of the students were also towards this direction as:

“Fluid systems application wasn’t gone over much in class, going over applications would help interest. One or two more lectures like this during the semester would be benefited to most students, as it helps with interest. This lecture was very insightful and broadened my view of fluid systems and application.”

“This lecture really showed me what microfluidics is and how to apply it. Knowing how you apply things is the best for students because it really shows you how this stuff will be used. Definitely inspired me to continue my education with this lecture. “

“I was intrigued by the lecture and feel that providing an explanation of the research being done really served to draw interest in this subject.”

We are also planning to have the microfluidics lecture and even more similar lectures earlier in the semester. Especially, demonstrations of fluid properties early in the semester might help drawing interest on the course as some students wrote down about this issue as:

“Great presentation, maybe earlier in semester next time.”

“I really enjoyed the lecture and now wish the basics of microfluidics was introduced sooner in the lecture.”

“The portion of applications, I think is the most interesting. Having this lecture possibly after our first midterm would be a good time because you can use it to appreciate what you are learning for the rest of the semester. Having labs with actual applications or hands on work would be interesting.”

After the lecture, most of the students (74%) are also willing to have a lab on microfluidics or substitute one of the current labs with a microfluidics lab. Almost all of the students (around 90%) also have high desire for hands on experience on related research and for seeing live demonstrations of the actual working devices. This might be challenging for such a big class and equipment requirements, but since there is a really big interest and demand we will put more effort on this issue for the next semesters. The final question was about the engineering curriculum in general and similarly almost 90% of the students want to have more application based course or lectures similarly embedded to other courses. It is clear that we should introduce
more applications to students during courses and have them involved in research activities as much as we can. The students’ comments agreeing with this argument are:

“Would like to see more machine/lab process in action (ex: video) of microfluidics.”

“Enjoyed the lecture and I am really interested in learning more/possibly getting involved with microfluidics.”

“I would like to have one or two more lectures involving some microfluidics and possibly nano.”

Conclusions

The microfluidics lecture based on one and half hour-long presentation composed of introduction, theory, design, applications, market and job information were successful in drawing significant interest on the topic. The results from the multiple choice survey and comments have clearly shown that majority of students found it very useful and they were happy to see applications of fluid mechanics, especially on a topic like microfluidics with the applications presented.

The content and organization of the lecture was found sufficient in general. Some students found the duration a little short considering the large amount of material mentioned in the presentation. We are planning to have the lecture separated into two lectures for better understanding for the next semesters. The market and job information was especially found to be very useful, which is not frequently included in engineering courses. In a similar manner, it can be really helpful to introduce job opportunities also at other classes, which might help students a lot for their career plans and decisions.

The main aim of the lecture was to introduce the world of microfluidics to the students and to draw interest on the topic by mentioning cutting edge applications like lab-on-a-chip devices. The students that answered to have interest in fluid mechanics and microfluidics have increased by 75%, the number of students who are planning to have a career on fluid mechanics and microfluidics have increased by 121%. This percentage increase is calculated based on the students’ responses in the survey that was performed after the lecture. This way of surveying might not be as descriptive as two separate surveys, one before and one after the lecture. Nonetheless, the increase was significant enough to say that the lecture drew significant interest and helped students start considering a career in microfluidics and related fields.

Questions about future direction for the Fluid Systems course and curriculum in general were also included in the survey. The results show that students have clear interest on having a lab on microfluidics. It might be challenging to develop a lab on microfluidics, because of the
complexity of microfluidic systems and fragile and expensive equipment required. However, we will try to develop a simple microfluidics lab in order to teach the basics to undergraduate students.

It was also obvious from the results and comments that students demand more applications introduced in the Fluid Systems course and in other courses; and even courses based on new trends, technologies and applications. This might be a problem specifically related with mechanical engineering, because very few applications can be introduced before senior level. However, this demand might be fulfilled similarly by assigning a few lectures on applications. Assigning some lectures on applications might not only solve the problem of lack of applications, it will also help students a lot for their career decisions.

The results we have obtained from this lecture and experience made us consider adding more similar material to the course content. We are planning to extend the content of the lecture with more applications, live demonstrations and more exciting devices for next semesters. An extended version of the lecture with more theory and information is planned to be taught also for the graduate level fluid mechanics course. We are also considering adding a few more similar lectures, like introduction to CFD, to introduce more applications and concepts.

References