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Impact of Computational Fluid Dynamics use in a First-Year Engineering Research Design Project on Future Performance in Fluid Mechanics

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Introduction

Students in the final term of the Fundamentals of Engineering for Honors program at The Ohio State Universtiy have the option to take a research and design project focusing on an introduction to nanotechnology and microfluidics, which is then applied to lab-on-a-chip (LOC) design. Students design, model, and manufacture a microfluidic LOC device to measure cell adhesion, then design a hypothetical LOC using microfluidics and nanotechnology. As part of this course, students are introduced to basic fluid mechanics principles and to computational fluid dynamics (CFD) software. Students may alternatively enroll in a robotics design and build project,[1] which does not contain fluid mechanics material. Many of the engineering majors later require students to take classes which focus further on fluid mechanics. This paper seeks to answer the question: *Does introduction to the subject of fluid mechanics including computational fluid dynamics (CFD) in a first-year engineering research and design course increase students comprehension and performance in subsequent major-required fluid mechanics courses?*

The course is intended to give first-year engineering students experience with research and design while teaching concepts such as cell adhesion, cellular response to shear stress, and microfluidics. Students are introduced to nanotechnology and lab-on-a-chip devices, fields of great interest to which they often would not otherwise be exposed until later in their undergraduate experience. Fluid mechanics is necessary for students to understand the topics to which they are being introduced and for them to interpret their research results. Students are given information on fluid mechanics theory in lectures and out-of-class materials, then complete guided worksheets to increase their understanding of the underlying principles of fluid mechanics. These worksheets use the Navier-Stokes equations to derive velocity profiles of cylindrical and rectangular channels. Students then create a simple computer program to calculate information about the flow profile in a rectangular channel based on the equations they derive.

CFD software is then introduced both as a tool for educational purposes (allowing the students to visualize the flow properties described in other course materials) and as a method to analyze flow-fields in their custom LOC devices prior to manufacture. ANSYS FLUENT (ANSYS Inc., Canonsburg, PA) was used until the Spring 2013 term, and SolidWorks Flow Simulation (Dassault Systèmes SolidWorks Corp., Paris, France) have been used in recent years. Students follow a written tutorial that introduces them to the CFD environment and briefly displays some of its capabilities. They later use the software to perform sensitivity analyses of the flow profile to microfluidic channel dimensions and to characterize the flow in their own custom-designed microfluidic LOC. These data are used to interpret the results of their experiments on yeast cell adhesion in their LOC device. The graphical interpretation offered by the CFD software aims to help dispel misconceptions about fluid flow and allows students to better visualize the flow.

This study was conducted under IRB exempt protocol # 2013E0570 in accordance with the Office of Responsible Research Practices.

Study Population

The study participants are all alumni of the honors first-year engineering program, which is open to first-year students that have been given 'honors' status based on high school achievement. In the first semester of the program (Autumn), students are introduced to problem solving methods, working in groups, and computer programming in C++ and MATLAB. The second semester (Spring) begins with an introduction to engineering graphics and computer aided design (CAD) software. The last 10 weeks of the term are spent on a design project- either a robot design-build course or an alternative nanotechnology research and design course.

The program had been in a quarter format until the 2012-2013 academic year. Under the quarter system, the first (Autumn) quarter was an introduction to engineering graphics, CAD software, group work, and problem solving methods; the second quarter (Winter) taught computer programming with MATLAB and C++; the spring quarter was devoted entirely to design projects, which were still nanotechnology or robot. Study participants had all completed the program within the last four years (Spring 2010 to Spring 2013). Approximately 1500 students fall into this category, as shown below in Table 1.

Table 1: Distribution of student participants by course and year

Year	Robot	Nano	Total
2010	307	39	346
2011	277	47	324
2012	293	61	354
2013	342	103	445
Total	1219	250	1469

Course Structure

The nanotechnology course develops skills in several key areas. Students are given a research prompt and are then responsible for the design, manufacture, and testing of a custom LOC device. After testing is completed, students give a technical slideshow presentation and participate in a judged poster competition. Comparatively, the robot course introduces students to various aspects of mechanical design: motors, statics, and strength of materials. The objective is to create an autonomous robot which is capable of completing a number of tasks on the competition course. The difference in course content attracts more students from biomedical engineering or chemical engineering majors to the nanotechnology and microfluidics course; students from mechanical and aerospace engineering enroll almost exclusively in the robot course.

With the conversion to semesters in the 2012-2013 school year, an inverted classroom structure was implemented. In this pedagogical model, the content remains the same but the instructional day is divided into two parts: preparation and application.[2-4] Table 2, at the top of the following page, shows the components and timing of a typical inverted class day. Students work on remembering and understanding (the lowest two levels of the Bloom's taxonomy)[5] with readings, guided videos, and quizzes prior to class; this leaves more classroom time available for the higher levels of Bloom's taxonomy, especially application. Students are given a short lecture to review the preparation work, then given guided activities or assignments to reinforce their learning. In a class such as this one where a large portion of the application requires specialized equipment, this is an important benefit to students. After class, students complete assignments and prepare for the next class.

Table 2: Typical Inverted Class Day Schedule

Before Class	During Class	After Class
• Preparation activity: Reading, video, tutorial, or problem(s) • Evaluation: online quiz or turned in solution	• Short lecture • Activities • Application assignments or lab	• Finish application assignments, open lab • Prepare for next class

The course consists of five main components: experimental microfluidics, nanotechnology research, group presentations on nanotechnology topics, a poster presentation on the microfluidic cell-shearing experiments, and an oral presentation on the hypothetical nanotechnology LOC. Respectively, these contribute about 50%, 20%, 10%, 10%, and 10% of the final project grade. The final poster and oral presentations are judged as part of a final competition to reward research quality and presentation skills.

The experimental microfluidics portion of the course asks students to design, build, and test a lab-on-a-chip device to test the adhesion of yeast cells under shear stress on patterned and non-patterned surfaces, based on work by Mercier-Bonin et al.[6] The 10 week research-design-build project educates students about biomedical devices utilizing microfluidics, microscale features, and nanotechnology. Students read technical papers in these fields, take lab tours, and gain hands-on experience with microscale devices. Readings discuss applications of nanoscale technology as well as techniques for developing and manufacturing nanoscale devices. Concepts such as biocompatibility, cost, and durability of material are discussed.

In order to design their devices and interpret their results, students are introduced to fluid mechanics and CFD software. Students watch short (1-15 minute) videos covering the basic principles of fluid mechanics over several days, and complete an accompanying worksheet for the derivation of a velocity profile across a cylindrical channel. Following their completion of this worksheet, students complete a guided worksheet for a rectangular channel during class, using the principles discussed in the videos and the cylindrical coordinates worksheet.

After completing the worksheets, students use their derived equations to write a program (using MATLAB, C++, or LabVIEW) to determine flow characteristics of an incompressible Newtonian fluid through a rectangular channel. Also after completion of these worksheets, students perform a two-part lab exercise designed to introduce them to CFD software. In the first part, students are provided with a computer model of a simple rectangular channel, through which they model pressure-driven fluid flow as shown in Figure 1, on the following page. They generate images of the static pressure, velocity profiles, wall shear stress, and particle pathlines. This is used to help corroborate the information students have learned from the videos and thus better understand both fluid mechanics in general and microfluidics as a whole.[7,8] Students also create an animation showing how fluid moves through the channel. The exercise is then repeated with a higher-quality mesh, and students are educated about the differences in meshes and which characteristics are important for a mesh. They are also shown how to determine whether a mesh produces realistic results.

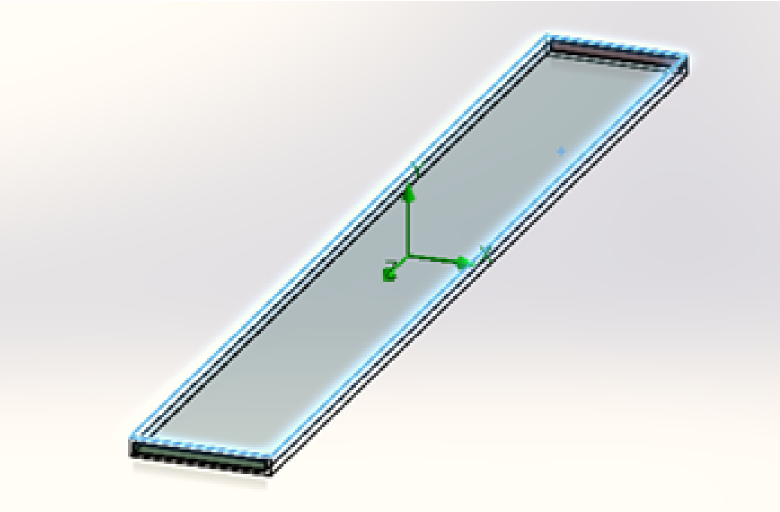


Figure 1: Rectangular Channel Model

In the second part of the laboratory, students model flow through a channel from a standard chip which is used in initial introductory lab experiments. The computer model of the channel is again provided (see Figure 2 below), and students find the same properties as in the simple channel, with an explanation of entrance length. Students compare the results from the CFD software to the output of their own programs, and discuss reasons for discrepancies.

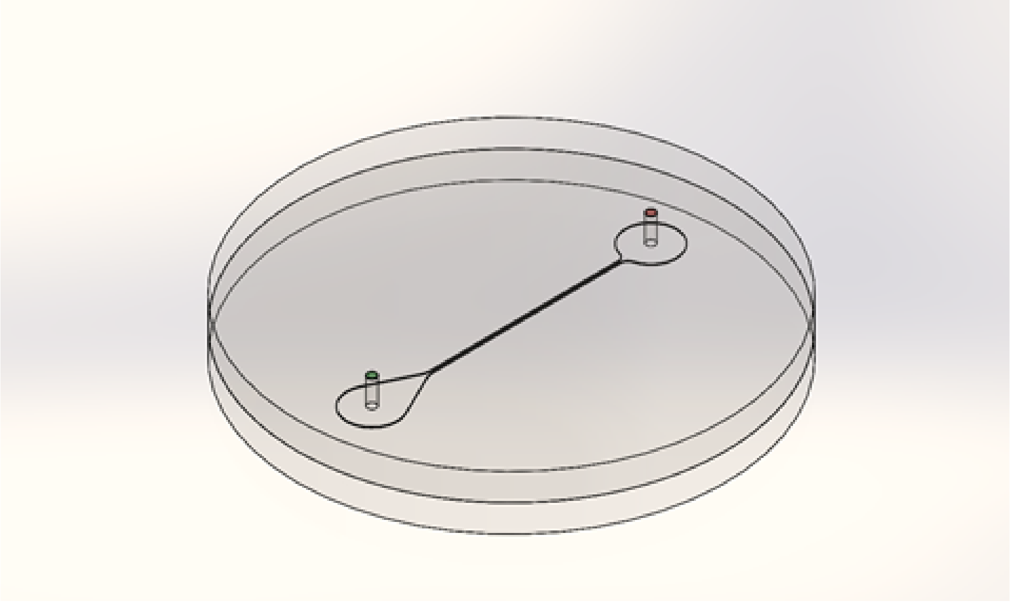
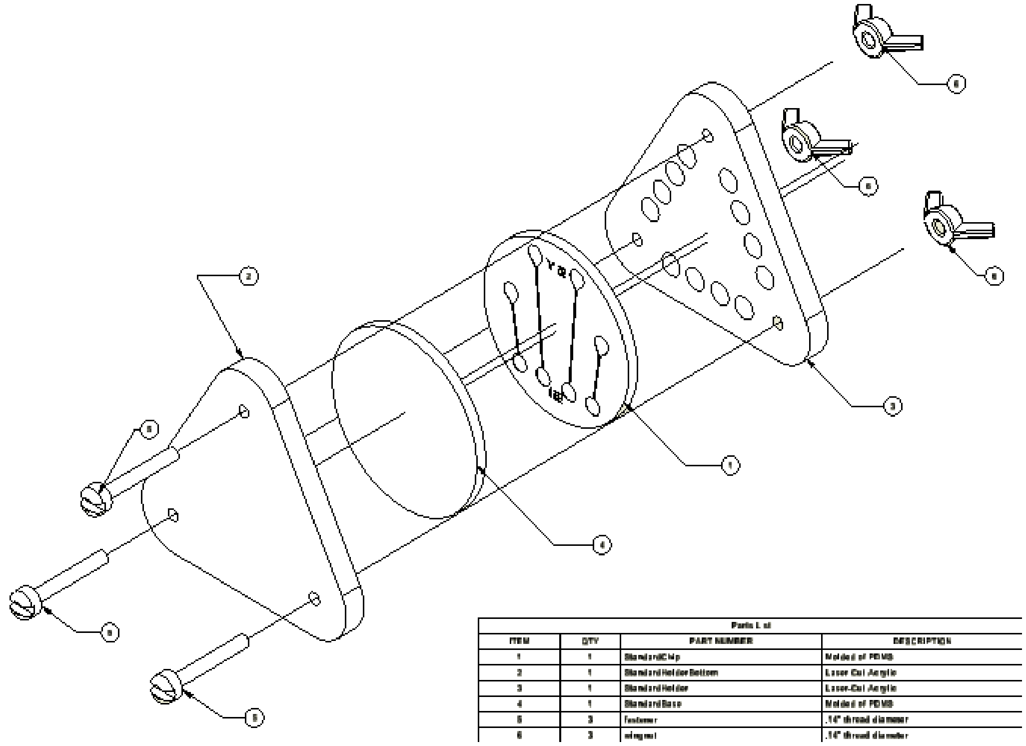


Figure 2: Standard Channel Model

Modified versions of the standard channel (in which the height of the channel is varied by a factor of 5%) are used in the following lab, in which students perform a sensitivity analysis and calibrate the channels on provided standardized LOC devices. These devices are two pieces of molded PDMS with 2-inch diameters, in a chip holder of laser-cut acrylic material, similar to the devices students create later in the course. Figure 3 below shows an example device provided to students in the course. The connection of LOC devices to the material already learned about microfluidics and fluid mechanics encourages students to engage more deeply with the topic.[9]



Parts List			
ITEM	QTY	PART NUMBER	DESCRIPTION
1	1	StandardChip	Molded of PDMS
2	1	StandardHolderBottom	Laser Cut Acrylic
3	1	StandardHolder	Laser-Cut Acrylic
4	1	StandardBase	Molded of PDMS
5	3	fastener	.14" thread diameter
6	3	wingnut	.14" thread diameter

Figure 3: Standard Chip and Holder Assembly

As students design their own devices, they model them using the CFD software to determine whether the proper flow conditions will be reached. Students can use this information to redesign their channels before manufacture or to potentially explain issues found after the manufacture of the chip.

Approach

To measure student performance and comfort level with fluid mechanics principles, alumni of the first-year program were surveyed via email with a link to a Qualtrics (qualtrics.com) survey about their understanding of fluid mechanics in subsequent major-required fluid mechanics courses. Only students that self-identified as being in majors that offer more courses on fluid dynamics were surveyed. These majors are: Aerospace/Aeronautical Engineering, Agricultural Engineering, Biological Engineering, Chemical Engineering, Ecological Engineering, Environmental Engineering, Food Engineering, Materials Science Engineering, and Mechanical Engineering.

Students were asked to self-evaluate their relative comfort level and performance in their major-required class compared to other students from the program who had chosen another option. Students who had taken the nanotechnology option were also asked to evaluate how helpful the CFD software had been in helping them understand theory discussed in the course and whether it had helped them dispel misconceptions about fluid flow. All students who were in a major requiring fluid mechanics were asked two questions reflecting basic fluid mechanics, to test whether the course had in fact been helpful in overcoming common misconceptions.

Grade data was separately gathered without identifying information using the Student Informational System (SIS). Data was gathered for all students having taken major-required fluid mechanics courses and one of the design course options from the honors first-year program. Not all majors had students from both the nanotechnology and robot courses; those majors were not used in determining relative performance. A non-usable number of students from the infrastructure option had taken a fluid mechanics course, so only the robot and nanotechnology courses were compared. Data was used for students who had completed the first-year engineering course between 2010 and 2012.

Results

At the beginning of the survey, students were asked to give their major. This information was then used to selectively survey students who were in a major requiring a fluid mechanics course. Students were also asked to provide the year in which they had taken their design project course and which project they had chosen. This data is shown below in Table 4. Based on Tables 1 and 3, response rates were 23.05% for robot, 23.20% for nanotechnology, and 23.08% from the total group. Not all students were asked each question; logic steps showed these questions only to those students in an appropriate major.

Table 3: Respondent Profiles

		Which option did you take?		
		Robot	Nano	Total
When did you take the course?	Spring 2013	84	25	109
	Spring 2012	77	17	94
	Spring 2011	53	10	63
	Spring 2010	67	6	73
	Total	281	58	339

Students were asked to use a five-point Likert scale to evaluate their understanding and recognition of basic fluid mechanics in their classes. A value of 1 was assigned to strong disagreement and a value of 5 was assigned to strong agreement. The average scores given by students from the robot and nanotechnology options were compared and are shown in Table 4, on the following page. Using a t-test in Microsoft Excel, the p-values for recognition and comfort were $2.29*10^{-6}$ and $6.84*10^{-5}$ respectively, which are both statistically significant, indicating that the responses for each design course are different.

Table 4: Student Responses on Understanding and Recognition
(* denotes statistical significance)

Question	First-Year Course	Avg. Score	P Value
I recognized the material on fluid dynamics when it was introduced in my major-required fluid mechanics course.	Nanotechnology	3.97	*(p=.00000229)
	Robot	3.02	
I was comfortable with the introductory course material during my major-required fluid mechanics course.	Nanotechnology	4.06	*(p=.0000684)
	Robot	3.51	

Students were also asked to agree or disagree with the statement "I was better prepared for my major-required fluid mechanics course because of my experience in [first-year honors design course number omitted] than students who had taken another [first-year honors program] design option." Among respondents who had taken nanotechnology, the average was 3.875; for robot students the average was 2.431. With a p-value of 7.16×10^{-9}, this was a statistically significant difference. The grade data gathered indicated that for classes taken by students from both the nanotechnology and robot courses, as shown in Table 5, below.

Table 5: Average GPA in Major-required Fluids Class

Robot	Nanotechnology
3.28	3.40

Again using a five-point Likert scale, students from the nanotechnology course were asked to evaluate the usefulness of the CFD software they had used in that class in dispelling any misconceptions they had about fluid flow phenomena and in helping them visualize theoretical concepts taught in the course. Results of this are shown in Table 6, below.

Table 6: Student Opinion on Usefulness of CFD Software

Question	Average Response Score
The CFD software used in the Nanotechnology course helped me visualize flow and better understand theoretical concepts discussed in the course.	4.00
The CFD software used in the Nanotechnology course helped me overcome any misconceptions I had about basic principles of fluid flow.	3.72

Students were then asked to answer two questions to gauge their grasp of basic fluid mechanics principles. These questions and the responses given by robot and nanotechnology students are shown in Table 7 on the next page.

Table 7: Current Understanding Assessment Responses (* indicates correct response)

<table>
<tr><td colspan="5">For fluid flow in a pipe or channel, static pressure _____ as velocity increases.</td></tr>
<tr><td></td><td>increases</td><td>decreases*</td><td>does not change</td><td>cannot be predicted</td></tr>
<tr><td>Nanotechnology</td><td>20 (55.6%)</td><td>11 (30.6%)</td><td>4 (11.1%)</td><td>1 (2.78%)</td></tr>
<tr><td>Robot</td><td>59 (39.9%)</td><td>58 (39.2%)</td><td>25 (16.9%)</td><td>6 (4.05%)</td></tr>
<tr><td colspan="5">For fluid flow in a simple pipe or channel, velocity is highest at the _____ of the pipe and shear stress is highest at the _____ of the pipe.</td></tr>
<tr><td></td><td>edge, edge</td><td>edge, center</td><td>center, edge*</td><td>center, center</td></tr>
<tr><td>Nanotechnology</td><td>--</td><td>--</td><td>31 (86.1%)</td><td>5 (13.9%)</td></tr>
<tr><td>Robot</td><td>4 (2.74%)</td><td>6 (4.11%)</td><td>131 (89.7%)</td><td>5 (3.43%)</td></tr>
</table>

Discussion

The first two questions, which asked students to self-evaluate their familiarity with and understanding of fluid mechanics, indicated that previous students of the nanotechnology course felt better about their experience in their major required fluid-mechanics course. When asked to evaluate their recognition of material in their fluid mechanics class, there was nearly an entire point of difference on a 5 point scale in favor of nanotechnology alumni, with previous nanotechnology students generally agreeing that they recognized the material in their major-required class, while robot alumni were approximately neutral on recognition. When evaluating their comfort level with the material, students who had taken the nanotechnology course agreed that they felt comfortable with the material while students who had taken the robot course were between neutrality and agreement.

Students who had taken the nanotechnology course were between neutrality and agreement (but more in agreement than neutral) on whether the class had helped them to be better prepared for their major-required course than students who had taken another option.

Students who had taken the nanotechnology course also achieved higher grades in their major required courses than students who had taken the robot option, indicating that the perception of higher familiarity given by the survey is reflected in performance.

When alumni of the nanotechnology course were asked to evaluate the usefulness of CFD as a tool to visualize flow and understand theory, they were in agreement that it had been helpful, with a Likert scale value of over 4. This may indicate that the exposure to CFD software was useful for students in their later classes, contributing to their improved performance compared to their peers who had taken the robot course.

When asked whether the CFD software used in the nanotechnology course was helpful in overcoming conceptual errors, students were between agreement and neutrality but closer to agreement that it had been helpful. However, questions asked of students showed worse or approximately equal performance on questions about common misconceptions when compared to students who had taken the robot option.

The incorrect responses on these questions indicate a failure to fully overcome root misconceptions that students hold about the principles of fluid mechanics. Similar problems have been found with heat and energy transfer principles,[10] where students' errors are a result of problematic categorization of physical principles. These can be especially difficult to overcome, even with demonstrated refutation of the concept. The recency of reiteration of the correct response in other classes and the frequency over a prolonged period of time with which the misconception is disproven typically has a marked effect on the overcoming of misconceptions.

There are several possible explanations for the discrepancy observed between student performance in their major required classes, their self-evaluation, and their performance on the evaluating questions. In the interest of avoiding survey fatigue, only two conceptual questions were asked of students, such that overall performance may not be accurately reflected by those questions. One of these questions related to the behavior of static pressure as fluid velocity through a channel increased. In the cell-shearing experiments performed in the nanotechnology class, students use pressure driven flows through their LOC. Since the increased pressure at the channel entrance causes an increase in flow rate, it seems possible that students were misinterpreting the question.

It is also possible that the improved performance among robot alumni is reflective of their later classes. None of the 20 aeronautical engineering students who had taken the nanotechnology course responded to the survey; this major showed the highest correct response rate to both questions. Only one of the 82 mechanical engineering majors who responded had taken the nanotechnology course; this major had the second highest correct response rate on the first question and the third highest for the second question. The major-required courses for these majors may be responsible for the apparent better performance of robot alumni compared to nanotechnology alumni.

Conclusions

Alumni of the honors first-year engineering program nanotechnology course generally had higher recognition of the material and felt more comfortable with their understanding of the material in their major-required fluid mechanics courses than students who had taken the honors first-year engineering program robot course option. The previous nanotechnology students credited the course with having better prepared them for their major-required course than the other options. This was reflected in the grades, which showed higher performance in the major-required fluid mechanics courses among nanotechnology alumni compared to robot alumni.

Students who had previously taken the nanotechnology course also were asked to evaluate the usefulness of the CFD software in that class. Students agreed that it was helpful in visualizing flow and understanding theoretical concepts. While they also claimed that the software had helped them overcome misconceptions about fluid flow, this was not reflected in their responses to questions designed to test common misconceptions about fluid flow. This may be due to the experimental setup students used in the nanotechnology course for their cell-shearing influencing their interpretation of the question or to the uneven distribution of majors among the nanotechnology and robot options respondents.

The honors first-year engineering program's nanotechnology course was successful in preparing students for their major-required fluid mechanics courses, as they both perceived themselves to better understand the material than their classmates and achieved higher grades than students who had instead chosen to take the robot course through the first-year program. Further work is needed to dispel misconceptions about fluid mechanics among students; although students feel that the CFD software is helpful in overcoming misconceptions and understanding flow, they still retain common misconceptions.

References

1. J. Beams, J. Radigan, P. Dutta, T. Pavlic, J. Demel, R. Freuler, E. Justen, M. Hoffman. “Experiences With A Comprehensive Freshman Hands On Course Designing, Building, and Testing Small Autonomous Robots.” ASEE Annual Conference and Exposition. 2003.
2. M. Lage, G. Platt, and M. Treglia, “Inverting the Classroom: A Gateway to Creating an Inclusive Learning Environment.” Journal of Economic Education, Vol. 31, No. 1, pp. 30 – 43, Winter 2000.
3. J. Strayer. “How learning in an inverted classroom influences cooperation, innovation and task orientation.” Learning Environ Res., Vol. 15, pp. 171–193, July 2012.
4. J. W. Baker. "The ‘classroom flip’: Using web course management tools to become a guide by the side," presented at the 11th International Conference on College Teaching and Learning, Jacksonville, FL, 2000.
5. L. W. Anderson, D. R. Krathwohl, B. S. Bloom. “A taxonomy for learning, teaching, and assessing.” Longman, 2005.
6. M. Mercier-Bonin, K. Ouazzani, P. Schmitz, S. Lorthois. “Study of bioadhesion on a flat plate with a yeast/glass model system.” Journal of Colloid and Interface Science 271 (2004) 342-350.
7. D. Pines. “Using Computational Fluid Dynamics to Excite Undergraduate Students about Fluid Mechanics.” ASEE Annual Conference and Exposition. 2004.
8. C. Sert, G. Nakiboglu. “Use of Computational Fluid Dynamics (CFD) in Teaching Fluid Mechanics.” ASEE Annual Conference and Exposition. 2007.
9. O. Onen, R. Guldiken. “Introduction of Microfluidics to Undergraduate Fluid Mechanics Courses.” ASEE Annual Conference and Exposition. 2012.
10. M. Prince, M. Vigeant, K. Nottis. “Development of the Heat and Energy Concept Inventory: Preliminary Results on the Prevalence and Persistence of Engineering Students' Misconceptions.” Journal of Engineering Education, Vol. 101, No 3., pp. 412-438.