Advances in Engineering Education

FALL 2016

Flippin' Fluid Mechanics - Comparison Using Two Groups

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ABSTRACT

A flipped classroom approach was implemented in an undergraduate fluid mechanics course. Students watched short, online video lectures before class, participated in active in-class problem solving sessions (in pairs), and completed individualized online quizzes weekly. In-class activities were designed to develop problem-solving skills and teach subject content. The instructor and assistants provided critical "just-in-time tutoring" during the in-class problem solving sessions. Comparisons were made with a simultaneous section offered in a traditional mode by a different instructor. Students in the flipped-classroom section demonstrated greater gains on the Fluid Mechanics Concept Inventory (pre-test versus post-test). Multivariate regression analysis revealed that students in the flipped-classroom section had a significant relative gain on the Fluid Mechanics Achievement Score, which was an aggregative measure of problem solving ability and conceptual understanding. Student feedback on the flipped-classroom section was very positive both in terms of the course format and their perceptions of the amount learned in the course.

Key words: Flipped Classroom, Fluid Mechanics, Concept Inventory

INTRODUCTION

Fluid mechanics is a cornerstone subject of undergraduate engineering education. Understanding the motion of fluids, including gasses, liquids, and non-Newtonian materials is integral to applications in many, if not most, engineering systems. This includes grasping the concepts of internal flows, such as flows in pipes and ducts, and external flows around moving and fixed objects such as vehicles and structures. The subject is also important to understanding natural flows such as river and ocean currents and atmospheric winds. In short, the applications of fluid mechanics are both important and ubiquitous.

Despite fluid mechanics centrality to engineering applications and resulting fundamental importance to engineering curricula, many students find the subject difficult and, as a result, show low levels of engagement and performance (Albers & Bottomley, 2011). Much of the subject material requires a high level of abstraction to effectively conceptualize flow configurations. Flow configurations can be particularly challenging to grasp as they are often three-dimensional and may also include variation in time. Furthermore, understanding these applications and performing the requisite problem solving requires successful application of vector and multivariate calculus, differential equations, and other types of advanced mathematics. Faced with these complexities, it is not uncommon for a student, being exposed to fluid mechanics for the first time, to be prone to discouragement and become disengaged (Bondehagen, 2011). Keeping students engaged and interested is a challenge for every instructor and is particularly important in classes wherein conceptually-difficult material is being introduced (Smith et al., 2005).

RESEARCH QUESTION: How do you keep students engaged in challenging classes while at the same time increasing conceptual understanding?

Active Learning is well supported in the literature of engineering pedagogy as a superior instructional method (Terenzini et al., 2001). To foster active learning and improve student performance and engagement, one of this study's co-authors flipped the classroom. In a flipped or blended classroom, students view course material outside the classroom and use class time to practice and apply concepts (Margulieux et al., 2014; The Chronicle of Higher Education, 2015). Outside of class, students may watch pre-recorded video lectures or learn course material through other instructional delivery methods (Fulton, 2012; Velegol et al., 2015). During class, students apply the material by doing labs, engaging in team-based problem-solving, or other types of practical application activities (McGee and Reis, 2012; Velegol et al., 2015). As an active learning approach, the flipped or blended classroom pedagogy is increasingly gaining traction in higher education, particularly in engineering disciplines (Mason et al., 2013; Bishop & Verleger, 2013). Advances in technology are further enabling this shift (Biddix et al., 2015).

In general, active learning increases student performance (Freeman et al., 2014). Active learning in the flipped classroom shows particular promise for increasing student engagement, knowledge retention, and practical skills—all areas of increasing focus for engineering education (Velegol et al., 2015). For instance, Catalano & Catalano (1999) suggested replacing the teacher-centered method of engineering pedagogy with an active learning approach that was student-centered and engaged students in the learning process (Felder & Brent, 2004; Prince, 2004). More recently, Albers & Bottomley (2011) recommended replacing in-class lecture time with activities that reinforce the concepts from lecture – a shift from teacher-centered instruction to student-centered learning. In further support of the efficacy of the approach, Velegol et al. (2015) reported a successful implementation of a flipped-classroom approach in an introductory engineering course and noted that the format allowed students to become active learners.

To test this instructional method, the authors designed a study to quantitatively and qualitatively assess the impact of the intervention on student performance in a required fluid mechanics course. This paper reports a comparison of two courses that offered equivalent fluid mechanics material with different modes of content delivery and strategies for in-class work.

DESCRIPTION OF THE INNOVATION

As in many other universities, fluid mechanics is a required course in the Civil Engineering (CE) and Environmental Engineering (EnvE) degree programs at the Georgia Institute of Technology (Georgia Tech). For many students, this course serves as the first introduction to the subject of fluid mechanics and is very similar to introductory courses taught in other Civil & Environmental Engineering departments as well as most Mechanical Engineering departments. In Georgia Tech's curriculum, the semester long, three-credit-hour course is intended for the first semester of junior year in both the CE and EnvE degree programs and typical enrollees include a mixture of juniors and seniors and a few sophomores. The course meets for 50 minutes of class time three days each week on a Monday, Wednesday, and Friday schedule. Specific topics covered in the course include Fluid Statics, Fluid Kinematics, Pressure Variation in Moving Fluids, Conservation Laws (Mass, Momentum, Energy, and Angular Momentum), Dimensional Analysis, and Boundary Layer Characteristics. The course learning outcome is that students demonstrate an ability to apply fundamental flow analysis techniques to fluid systems.

In the traditional course format of lecture and examination, students performed poorly in this course. In the instructor's observation, students passively listened to the traditional lecture even with significant effort to encourage participation and discussion. Class attendance was mixed and particularly poor on Fridays. Performance on both homework and examinations was below expectations. Students struggled to complete the problems on the homework sets assigned each week either failing to adequately apply concepts and solve problems or parroting a previous solution obtained from the internet or from unofficial archives maintained by student groups. All of these factors proved problematic for knowledge retention. For students struggling to complete the problems on their own, they received support only if they visited the instructor's office for help. For students copying solutions available from previous semesters, they failed to develop basic skills of problem solving. Both instructors and students were unsatisfied. Students often made comments on post-course surveys such as "examination questions were much more difficult than the homework problems or lecture examples." From the instructor's perspective, the problem-solving exercises on the examinations were at the same level of difficulty as the homework assignments. And, many of the lecture examples were, in fact, examination questions from previous semesters. This course format had failed to provide an environment in which students could consistently obtain a depth of understanding of the material and thereby gain confidence in range of problem-solving exercises. With these observations as a backdrop, the instructor started the process to overhaul the course format. The motivation for trying a flipped-classroom approach was driven largely to engage students in the subject and to enhance problem-solving skills through active participation.

Flipped classroom

The flipped-classroom approach that was implemented for the first time in Spring 2013 semester is described in the flowchart shown in Figure 1. Students watched online videos before the class session. To capitalize on the content and style that had been developed during previous course offerings, the instructor selected the video lecture approach and recorded his own lecture videos. The videos were recorded without an audience using the Tegrity recording software (McGraw-Hill Higher Education, Burr Ridge, Illinois) in the instructor's campus office. The recordings were stored on servers at Georgia Tech's Professional Education Division with good technical support. Examples of technical support included maintaining the servers, managing software and licenses, and responding to questions and problem-reports. In this regard, Calderon et al. (2012) reported that sufficiency of the university resources was the strongest predictor of student satisfaction with blended courses.

A tablet PC provided the primary recording medium. The Open Sankoré software (http://open-sankore.org/) was used as a virtual white board and the instructor predominately hand-wrote the lecture content using the stylus in a manner that was consistent with a traditional lecture on a classroom white board. A handwritten format that progressed with the recording was employed, rather than pre-prepared slides, to create a pace that facilitated verbal description by the instructor, allowed the students to write notes, and provided time for the students to absorb the material. Simultaneously, a webcam recorded the instructor's face and upper torso and additionally contained a microphone to record the audio content. During playback, the webcam recording played synchronously in a small window on the screen next to the main window showing the tablet PC recording. The audio content was again consistent with that delivered during a traditional lecture presentation, essentially describing the principles or explaining the steps of example analysis. Students could

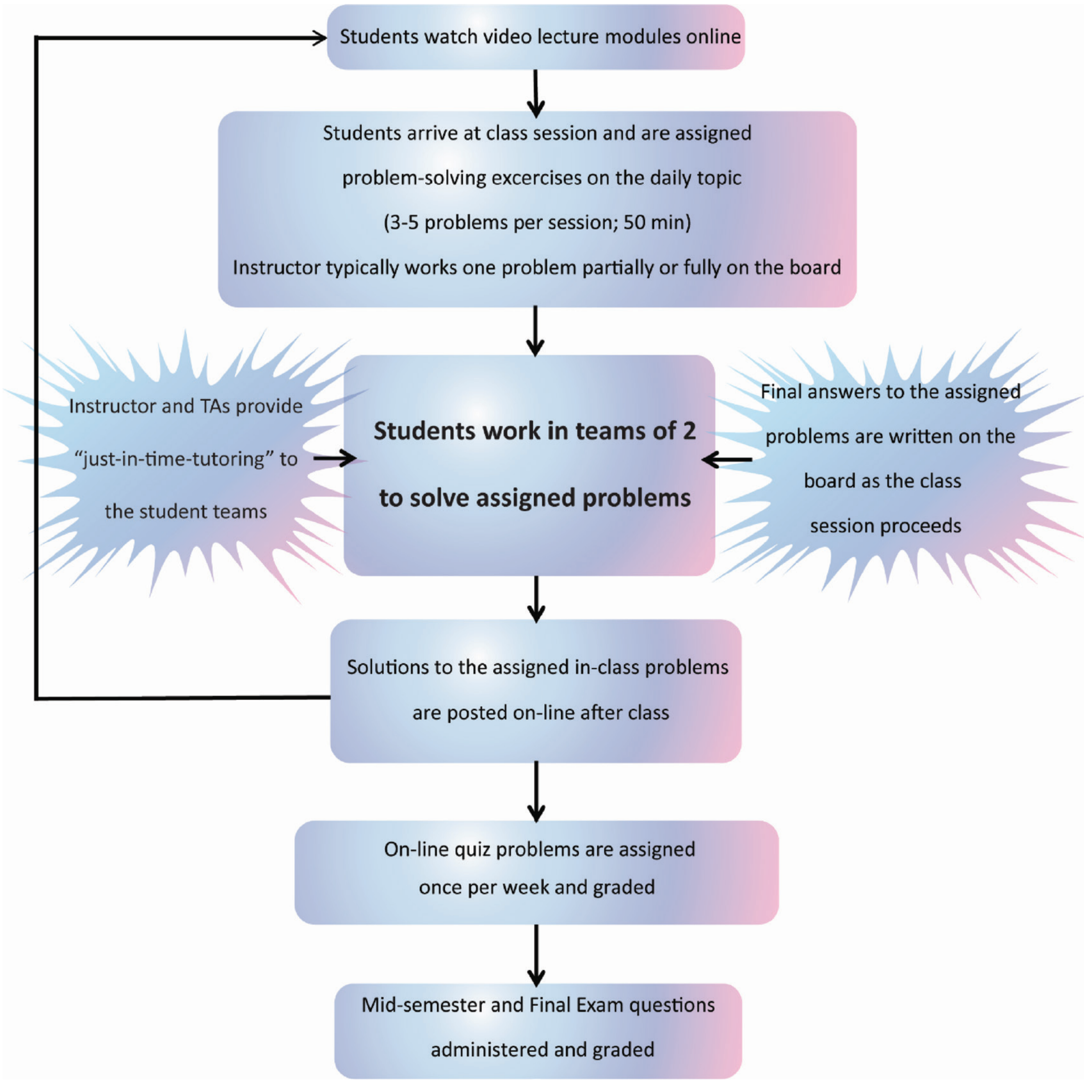

Figure 1. Sequence and description of the flipped-classroom course format.

expand the main window to full screen, if desired. Students had control to pause, rewind, and fast forward the recording. They also could play the recording at a faster speed, up to two times the recording speed. The software facilitated making bookmarks and notes for students wishing to annotate the recording for future reference.

A total of 74 lecture videos were recorded. The average length of the recordings was 11.6 minutes. The video lectures followed the content of the instructor's lecture notes developed in previous traditional-lecture offerings of the course with the difference that the content was divided into smaller segments. The presentation was purposely highly focused, and it was presented at a brisk pace due to the control that students maintained during playback. The content consisted of a theoretical presentation of the topic and example problem-solving exercises. Thirty-nine of the lecture videos consisted of example problem-solving exercises, in which the instructor explained the analysis step-by-step. In advance of a particular meeting session, students were assigned between 0 and 5 recordings to watch, which was clearly explained on the course syllabus and class website. Students typically recorded handwritten notes based on the lecture videos. The schedule provided in the course syllabus also directed students to the relevant section(s) in the textbook (Munson et al., 2013).

During the course design, great emphasis was placed on developing effective in-class activities. Since fluid mechanics, and engineering mechanics in general, requires effective problem-solving techniques, the primary focus of the in-class activities was to develop problem-solving skills and proficiency. The class met 3 times per week for 50 minutes. During the class sessions, students worked in collaborative teams of two on active problem solving. The purpose of creating the teams was to encourage the students to work and collaborate together. A team size of two was selected to create a dynamic in which each student was engaged – for instance a team of three could easily lead to one member of the team being "left out" of the conversation. Students were allowed to choose their partner from a sub-group of the class population. The sub-groups were formed based on incoming GPA (without their direct knowledge of the criteria) with the motivation to partner students with comparable performance in previous courses. The purpose was to create teams that were fairly balanced for collaborative communication and to avoid scenarios where a weaker student was simply copying a stronger student without actively engaging in the challenges of the problem-solving exercise. Partners remained together for the full semester.

The instructor assigned 3 to 5 problem-solving exercises per session to be solved during class (number depended on the length and complexity of the problems). The problems consisted of examination questions from previous semesters and homework-style questions written by the instructor or selected from a textbook. Personalized white boards (32" x 21"), along with markers and erasers, were provided to each team to create a physical space for the students to collaborate via sketches and analysis. In total, 124 problem-solving exercises were assigned for the in-class sessions during the semester. The problems were directly linked to the topic of that particular session and logically connected to the assigned video lectures. The problems were generally sequenced from novice-level to more-advanced. For more substantial topics (such as Conservation of Momentum, for instance), two or more sessions were devoted to provide more depth of coverage and more problem-solving experience for the students. Often the instructor worked one exercise on the board either partially or fully at the start of the session. This allowed for additional problem-solving presentation beyond the recorded video lectures, started the daily session with a collective "inertia" among the students, and allowed the students to naturally ask questions about the particular problem, the video lectures, or the topic in general. On occasion, videos and photos (i.e., flow visualization) were shown and discussed in class to provide context and motivation for the fluid mechanics principle or application.

As the students worked on solving the remaining exercises, the instructor and 2 graduate assistants roamed the room interacting with the student teams. This interaction was best described as "just-in-time tutoring" because students often asked questions about specific points in the analysis on which they are stuck or unclear. In the event that numerous student teams asked similar questions, the instructor would spend a few minutes explaining and clarifying the issue on the board for the entire class. It was common for students to use laptops, tablets, or other mobile devices during the class session to reference the online textbook and other sources for equations, tabulated data, and example exercises. Final answers to the in-class problems were written on the board as the session proceeded so students could confirm their answers. No credit was given for the in-class problem solving. However, attendance was recorded each session and 10% of their final grade was dependent on attendance. To receive the attendance score, students must have 2 or fewer unexcused absences during the semester. In the instructor's observation, the lack of graded credit for the in-class work was a big factor in the success of the sessions because students did not feel pressure to get the work done or deliver the correct answer. Rather, they focused on learning the topic with the support of the instructor and teaching assistants and with the mindset of preparing for the upcoming online quizzes and examinations.

Student teams showed a tremendous range of proficiency during the in-class problem solving sessions. Some teams finished all of the problems quickly, whereas other teams completed only one problem during the session. And, of course, individual team performance varied session-to-session. For students entering with a strong understanding of a subject, they finished the problems quickly and gained the repetition and confidence needed for mastery. For students struggling with a subject, completing even one problem correctly during the session indicated that they figured out a problem-solving skill or concept that they were missing at the start of the session. In this regard, the course format met individual students at their level of understanding and revealed to the instructor where individual students needed help.

Online quizzes were assigned each week, and students completed them outside of the class sessions. Eleven quizzes were assigned for the total of 55 graded problems. The WileyPlus online system was used for the quizzes. An attractive feature of the system was that each student received a unique set of parameters for the same exercise. Hence, students were unable to directly copy from the potentially-available solution manual or from a classmate. The system also provided links from the assigned problems to the relevant sections of the electronic textbook. Students were permitted 3 attempts to earn credit for a correct solution. After submitting the correct solution or exhausting the 3 attempts, the published solution to the problem became available to the student in PDF file format.

A class website was designed to facilitate access to the course materials. Due to the substantial volume of electronic materials and the detailed sequence of activities, the instructor viewed it as critically important to organize the materials in a manner that was easy for students to navigate and locate the correct materials at the right time. The motivation was to create an environment where students could focus on learning, rather than searching for materials or getting frustrated by unsuccessful searches. The website organization mirrored the course schedule provided in the syllabus. Individual folders were created for each meeting session. Links to the online video lectures that the students were expected to watch in advance of that session were available in the folders to eliminate ambiguity about the expected preparatory activities. The in-class problem-solving exercises were also posted in advance in a PDF file format for those students wishing a preview. After each class session, handwritten solutions to the in-class problems were posted in the corresponding folder in PDF file format. Links to the online quiz assignments were also established in the folders corresponding to the due date.

Primary student assessment consisted of three semester examinations and a final examination. The format of the examinations was problem solving exercises that were manually graded by the instructor. Student examinations were assessed to gauge the student's ability to:

1. identify an effective approach to the problem-solving exercises,
2. set up the problem-solving technique including a sketch, if needed,
3. correctly apply the correct principle(s) for the analysis, and
4. perform the calculations to produce the solution.

Traditional classroom

The class met for three 50-minute lectures per week. The lecture format consisted primarily of the instructor writing on the whiteboard. The content included explanations of the principles followed by application in example problem exercises, following the classic sage-on-the-stage paradigm. Videos and photos were shown and discussed on occasion to provide context and motivation. Students listened to lecture, typically took notes, asked questions, and answered questions posed to the class by the instructor. Attendance was neither required nor recorded. The instructor provided file share materials via a class website.

The topical coverage was identical to the flipped-classroom section described above, and the same textbook was employed. Students were given weekly homework assignments using the same online WileyPlus system described above. Ten homework sets were assigned for a total of 65 graded problems. Primary assessment consisted of three semester examinations and a final examination.

The format of the examinations was problem solving exercises that were manually-graded by the instructor with the same assessment criteria described above.

STUDY DESIGN AND ASSESSMENT

During the Spring 2014 semester two sections of the Fluid Mechanics course were taught in parallel. The flipped-section was offered MWF 11:05-11:55 and the traditional section was offered MWF 12:05-12:55. The classrooms were in the same building with nearly identical size, furniture, and A/V equipment. The instructor for the flipped-classroom section had 16 years of university-level teaching experience. The instructor for the traditional section had eight years of university-level teaching experience. Both instructors had taught the fluid mechanics course on numerous previous occasions. Both instructors consistently received teaching evaluation scores above the Institute-wide average. The instructors followed an identical course outline, had previously shared lecture materials, and had a similar presentation style in the traditional lecture format.

Students completed the Fluid Mechanics Concept Inventory (FMCI) Examination (Martin et al., 2003) during the first week of class and again during the final week of class (herein after referred to as "pre-test" and "post-test", respectively). The FMCI was a validated instrument designed to assess the degree to which students understood the essential knowledge in an undergraduate fluid mechanics course (Martin et al., 2003). Although the FCMI did not directly measure problem-solving skills, Martin et al. (2003) noted that students would not be able to perform effective problem solving without correct understanding of fundamental concepts. The FMCI Examination consisted of 30 questions with multiple choice answers that required minimal computation. The FMCI was selected due to the fact that its conceptual nature allowed administration pre- and post-test for subsequent comparison of results. The FMCI Examination was not announced in advance on either occasion in either section. The FMCI Examination was administered by a neutral third-party, and the instructors did not review the content of the examination in advance.

The instructors employed an identical Final Examination that consisted of five problem-solving exercises covering the breadth of the course. For the purpose of this study, a neutral third-party graded both sets of final examinations using a fixed rubric to provide a uniform assessment across sections.

During the eleventh week of class, students in the flipped-classroom section were asked to anonymously complete a survey (handwritten; administered in class) to provide feedback on their perceptions of the course format. The survey included the following questions:

- What aspects of the flipped-classroom format do you prefer over a traditional style course?
- What aspects of a traditional style course do you prefer over the flipped-classroom format?

- Do you find the video lectures to be helpful? More or less so than a traditional classroom lecture?
- At what moment in the class did you feel most engaged with what was happening?
- At what moment in the class did you feel most distanced from what was happening?
- Would you recommend this course format to a friend?

During the final three weeks of the semester (including final examinations week), students submitted the online Course-Instructor-Opinion-Survey (Institute-administered) on a volunteer and anonymous basis.

RESULTS

The flipped-classroom section had 39 students, and the traditional section had 40 students. The incoming GPA, total number of credit hours, and number of credit hours completed at Georgia Tech (i.e. excluding transfer, International Baccalaureate, or Advanced Placement credits) were not significantly different between the student populations in the two sections (Table 1). This indicates that the groups entered the course with a similar level of university-level educational experience and performance. The student population in the flipped-classroom section included 30% Environmental Engineering and 70% Civil Engineering majors, and the traditional section included 17.5% and 82.5%, respectively. The student population in the flipped-classroom section included 35% female students, and the traditional section included 22.5% female students.

Student Performance

The results of the FMCI Examinations are shown in Table 2. A subset of data for 21 students in each section was included in the t-test analysis. The subset groups corresponded to those

	Traditional	Flipped Classroom	*p*-value (Traditional vs. Flipped)
N	40	39	
Incoming GPA	3.12 ± 0.07	3.23 ± 0.08	0.35
Total number of Credit Hours completed prior to course	92 ± 2.9	86 ± 2.9	0.15
Number of Credit Hours completed at Georgia Tech prior to course	59 ± 4.8	53 ± 3.7	0.29

Table 1. Student population characteristics for two groups. Reported values are mean ± standard error of the mean.

	Traditional	Flipped Classroom	*p*-value (Traditional vs. Flipped)
N	21	21	
Pre-test	34.8 ± 2.2	36.0 ± 2.4	0.695 ($d = 0.12$)
Post-test	40.4 ± 2.3	49.8 ± 3.0	0.017* ($d = 0.77$)
***p*-value** (Pre- vs. Post-test)	0.024* ($d = 0.56$)	< 0.001* ($d = 1.12$)	

* indicates significant result (p-value < 0.05). The Cohen effect size parameter d is shown in parentheses where $d = 0.2$, 0.5, and 0.8 are considered small, medium, and large effect size, respectively.

Table 2. Comparison of pre-test and post-test Fluid Mechanics Concept Inventory (FMCI) Examination scores (t-test). Reported values are mean ± standard error of the mean.

whom provided consent for their data to be used in the study and whom also completed both the pre-test and post-test FMCI. In the pre-test FMCI, the average score among the flipped-classroom students was slightly higher than that among the traditional-classroom students (Table 2). However, the difference was not significant, which suggested the student populations entered the semester with a comparable understanding of fluid mechanics concepts. The average score on the post-test FMCI was significantly higher in each section compared to the average score on the pre-test FMCI for that section (Table 2). This result indicated that students in each section gained understanding of fluid mechanics concepts during the semester, as expected. Comparison of sections indicated that the gain in the average score among the students in the flipped-classroom section was significantly greater compared to that for students in the traditional section (Table 2). The Cohen effect size parameter shown in Table 2 indicated the relative size of the significant differences.

The average score on the common final examination was greater among the students in the flipped-classroom section (74.4 ± 2.4; mean ± standard error of the mean) compared to the students in the traditional section (67.7 ± 3.0), but the result was only marginally significant (p–value = 0.083). These results contrasted those reported by McClelland (2013) for an undergraduate fluid mechanics course. In that case, the study found that the average final examination score among students in a flipped classroom section was lower than the average score in a traditional section.

Regression analysis was used to control for differences among students and to quantify the effect of the flipped classroom approach. The dependent variable was the sum of the students' final examination score and post-test FMCI score, which we called the "Fluid Mechanics Achievement Score" (possible range 0 to 200). In this analysis, student data for both groups were pooled

Variable	Mean	Standard deviation	Minimum	Maximum
FMCI pre-test score (0 - 100)	35.4	10.3	13.3	63.3
Male student dummy (1=Male; 0=Female)	0.78			
Section dummy (1=Flipped; 0=Traditional)	0.50			
Major dummy (1=Civil, 0=Environmental)	0.76			
Incoming GPA (0 - 4.0)	3.33	0.45	2.22	4.00

Table 3. The independent variables predicting students' Fluid Mechanics Achievement Score (aggregate measure of problem solving on final examination and conceptual understanding on FMCI). N = 42 consisting of 21 from each section.

and a variable was established to identify the section for each student. Following a power analysis (Cohen 1988) that showed the data were not skewed or kurtotic, combinations of every available group of 5 independent variables were tested to identify the group of variables that demonstrated the best ability to describe variability in the dependent variable. The identified group of independent variables was 1) pre-test FMCI score, 2) whether the student was male (vs. female), 3) whether the student's major was Civil Engineering (vs. Environmental Engineering), 4) whether the student was in the flipped-classroom section (vs. in the traditional section), 5) and incoming GPA (Table 3). The R-square value equaled 0.455 indicating that the included variables explained 45.5% of the variation in the dependent variable. Of the five independent variables, only three revealed significance (Table 4). Note that the non-significant variables must be included in the regression to yield the reported R-square value, but their individual influence should not be interpreted due to the non-significant result. Of the significant variables, both pre-test FMCI score and incoming GPA indicated a positive contribution to the dependent variable. It was not surprising that students who had performed at a high level in previous courses or entered the course with a greater conceptual understanding of fluid mechanics performed better at the end of the semester as measured by the Fluid Mechanics Achievement Score. The third significant variable was the section, and the results indicated that being in the flipped-classroom section contributed a gain of 14.5 points to the Fluid Mechanics Achievement Score (out of 200).

Student Feedback

In post-course surveys asking students for their response to the format, students expressed a marked preference for the flipped classroom design. Overall, student feedback was very positive both regarding the class overall as well as various components, such as the in-class sessions and

Variable	Unstandardized Coefficients	Standardized Coefficient	*t*	Significance
FMCI pre-test score	9.559	0.313	2.242	0.032
Male student dummy	–3.896	8.718	–0.447	ns
Section dummy	14.539	6.353	2.289	0.028
Major dummy	-0.374	–0.006	–0.046	ns
GPA	23.363	0.390	2.632	0.013
(Constant)	9.599		0.386	

Table 4. Summary of regression analysis for the independent variables predicting students' Fluid Mechanics Achievement Score (ns = not significant).

video lectures. Several students made similar global comments about the flipped format as the one below:

> "This has been a phenomenal experience that changed my thoughts about online lectures. I would never want to replace the in-class experience that I had in combination with the online lectures. I am more than thankful for this experience, because I don't believe I would have understood anything without it."

Similarly, regarding the goals for student learning in the flipped classroom, students often described the experience as "extremely effective," as one student commented: "Overall, I feel that I have learned the material and better problem solving techniques than in traditional lectures." These sentiments were echoed consistently, "I like the method and I think it played a critical part in my success in the class." It was also noted that the students found it easier to be engaged, "I really enjoyed coming to class each time. It was much easier for me to get excited about coming to actively solve problems rather than coming to listen to a lecture."

The responses to the question about recommending the flipped-classroom format included 32 "yes", 2 "no", and 2 "maybe" responses out of 36 submitted surveys, which was an 89% positive response. Many of the responses were very enthusiastic in support of recommending to a friend.

Several themes emerged from the survey results. Students liked the video lectures because 1) lecture content was highly focused in short modules, 2) they could watch them anytime and repetitively (hence providing flexibility), 3) they could "absorb information" at their own pace (i.e., pause, rewind) and in particular could re-watch challenging sections, and 4) there were no rushed running-out-of-time scenarios at the end of the lecture. The student comments also highlighted the limitations of the traditional lecture format, specifically the inability to re-watch challenging or missed sections. Many students echoed what one student commented, "I like that I can re-watch the lessons as many times as I need to to fully understand the course material."

Students appreciated the value of the in-class team problem-solving sessions due to their perception that the active participation better prepared them for the examinations. For instance, one student commented "problem solving (especially in an engineering or a math-related class) is the best way to truly understand the material." And students perceived the format as being linked to their grades, for instance, "the in-class problems are really good practice and make studying for tests easier." They also appreciated the opportunity to ask the instructor and teaching assistants for immediate (just-in-time) help. Not surprisingly, students indicated that they were lost and "most distanced" from the course when they failed to watch the video lectures in advance.

With regard to class attendance, 96% of students in the flipped-classroom section reported (in the Course-Instructor-Opinion-Survey) that they attended more than 90% of the class sessions. In contrast, 89% of students in the traditional section reported that they attended more than 70% of the class sessions, and only 67% reported that they attended more than 90% of the class sessions. This difference was presumably driven, in part, by the differences in the attendance policies for the two sections. Further, it could be conjectured that the flipped-classroom format encouraged student attendance based on the other data points, including student achievement, engagement, and reported satisfaction.

Figure 2 shows the student-reported data on the Course-Instructor-Opinion-Survey for number of hours spent per week on the course. The largest differences were at the low end, where the fraction of students spending 0-3 hours was greater for the traditional section and the fraction spending 3-6 hours was greater for the flipped-classroom section. This result suggests that the flipped-classroom format engaged students who otherwise might have been disengaged in the course (if one equates spending 0-3 hours per week with disengagement). A small number of the hand-written surveys expressed an issue of increased time commitment in the flipped-classroom format. Substantially increasing the number of hours per week did not appear to be a valid concern based on the data in Figure 2, however. Rather, the manner in which students were spending their time outside of class shifted instead of increasing the total time spent. In the traditional section, students spent time struggling on their homework assignments and reviewing the textbook. In contrast, students in the flipped section spent time watching the video lectures and completing the online quizzes that covered material with which they had previous problem-solving experience in-class. Students in the flipped section reported verbally and in the surveys that they had an easier time solving the online exercises after gaining experience with similar in-class problem-solving exercises. The flipped-classroom students also had to prepare in advance of the class sessions, and had to take greater responsibility for learning the material,

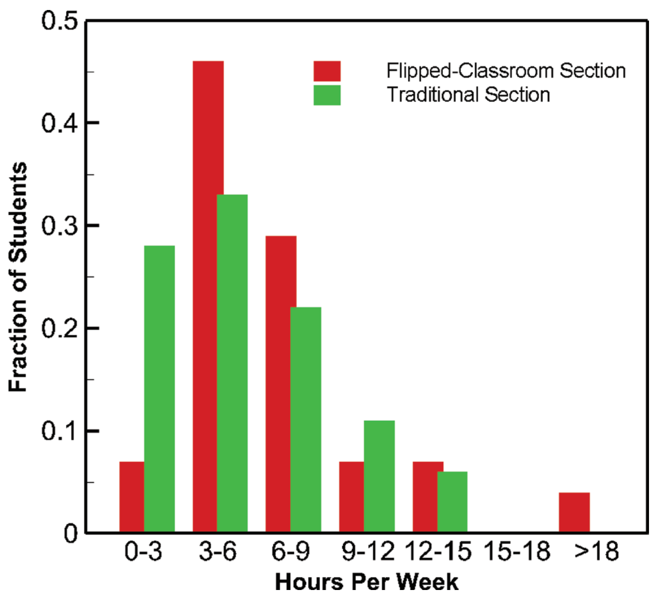

Figure 2. Student-reported hours per week spent on the course. Data are from the Course-Instructor-Opinion-Survey (CIOS) and are presented as the fraction of students in the section reporting for each range of number-of-hours. The number of responses is shown in Table 5 for each section.

which may explain the perception of the small number of students who indicated a concern about increased time commitment.

Table 5 shows results from the Course-Instructor-Opinion-Survey. For this survey, the Institute provided only the mean of the students' responses, hence statistical comparisons could not be performed. The first five questions related to the effectiveness of the instruction, which was influenced by the students' perceptions of the course format and the instructor. The flipped section had a higher mean for each question. Of particular note, the results indicated that the flipped-classroom format was effective at stimulating interest in the topic. Also, there was a large difference in the response to the query about the helpfulness of the feedback on assignments. Since both sections employed the same online system for the homework/quizzes, the difference appeared to be a consequence of the feedback received during the in-class problem solving sessions, which was a direct result of the differing course format. The second five questions related most directly to the course itself. Mean values for the last four questions shown in Table 5 were all higher for the flipped-classroom section, which indicated students felt that they learned more and that the course format was effective.

Variable	Traditional	Flipped Classroom
Number of Responses	18	28
Instructor's clarity in discussing or presenting course material. 5: exceptional; 1: very poor	4.4	4.8
Instructor's level of enthusiasm about teaching the course. 5: extremely enthusiastic; 1: detached	4.0	4.8
Instructor's ability to stimulate my interest in the subject matter. 5: made me eager to learn more; 1: ruined my interest	3.8	4.7
Helpfulness of feedback on assignments. 5: extremely helpful; 1: not helpful	3.5	4.7
Considering everything, the instructor was an effective teacher. 5: strongly agree; 1: strongly disagree	4.1	4.8
Rate how prepared you were to take this subject. 5: extremely well prepared; 1: completely unprepared	3.9	3.8
How much would you say you learned in this course? 5: an exceptional amount; 1: almost nothing	4.3	4.8
Degree to which activities and assignments facilitated learning: 5: exceptional; 1: very poor	3.9	4.7
Degree to which exams, quizzes, homework (or other evaluated assignments) measured your knowledge and understanding. 5: exceptional; 1: very poor	3.9	4.6
Considering everything, this was an effective course. 5: strongly agree; 1: strongly disagree	4.1	4.9

Table 5. Summary of results for the Course-Instructor-Opinion-Survey (CIOS). Mean scores are for a 1 to 5 scale, as defined for each questions.

CONCLUSIONS

The implementation of a flipped-classroom approach to an undergraduate fluid mechanics course required a dramatic shift in the roles of the students and instructor in the classroom and in the course overall. The shift was consistent with many previous flipped-classroom examples and constituted moving from a sage-on-the-stage model to a guide-on-the-side model. According to student feedback and the instructor's perceptions, the interactive in-class problem-solving sessions were the key aspect of the course design. The in-class activities were carefully designed to develop problem-solving skills via active engagement, to teach the subject via an organized sequencing of the course content, and to develop student inquiry skills by strongly encouraging students to interact among themselves and with the instructor and teaching assistants. As a result of the course design, students in the flipped-classroom section were actively engaged in 179 problem-solving exercises (124 in-class problems plus 55 quiz problems) in contrast to the 65 homework problems in the traditional section. This contrast in the number of problem-solving exercises was achieved without a substantial change in the student-reported number of hours per week spent on the course (Figure 2). The conclusion is that the implementation of the flipped classroom pedagogy, as described, was a highly effective means to implement active learning strategies and improve engagement in a core engineering mechanics course.

The study compared achievement results with a parallel section of the same course offered in a traditional format. Student achievement was superior in the flipped-classroom section as measured by comparing pre-test and post-test FMCI Examination scores, the average final examination scores (although only marginally significant), and a multivariate regression analysis. The greater achievement on the conceptual aspects of the material (as measured by FMCI and Fluid Mechanics Achievement Score) was particularly pleasing because the design of the in-class activities was primarily focused on problem solving. The results indicated that students gain understanding of the concepts in parallel with developing problem-solving skills, which was consistent with the study reported by Hake (1998). It was also consistent with the observation of Martin et al. (2003) that students must understand the fundamental concepts to effectively perform problem-solving. Limitations of the study included issues related to the potential influence of innate differences between the instructors and of other factors of the course that cannot be replicated exactly to isolate the innovation. Further, given the relatively small sample size of this study, it would be highly beneficial to augment with additional data in future studies.

Student feedback on the flipped classroom format was overwhelmingly positive. Students appreciated the control and flexibility that the course format offered. They also appreciated the interactive nature of the in-class active problem-solving sessions and the ability to ask for and receive just-in-time tutoring help. At the end of the course, students in the flipped-classroom section reported a high-level of learning of the course material and considered the course as highly effective. Students in the flipped-classroom section also reported that the course had highly stimulated their interest in the subject.

ACKNOWLEDGEMENTS

Financial support from the Georgia Tech College of Engineering Dean's Office and the Speedwell Foundation are gratefully acknowledged. The research was conducted under IRB Protocol #H13458. Thanks to Aaron True, Anna Skipper, David Young, and Seongyu (John) Jung for their assistance in the classroom. Special thanks to Dr. Jian Luo for allowing his class to be used as a comparison group. Thanks also to George Wright and the technical support staff at Georgia Tech's Professional Education Division.

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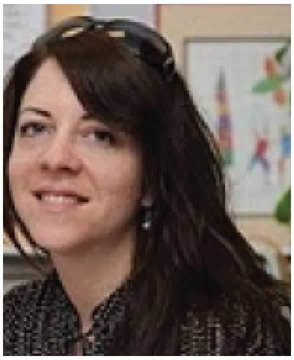

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