A Challenge-based Unit with a Hands-on Demonstration for Teaching Momentum in Undergraduate Fluid Mechanics

M.R. Myers* and H. Luo†

Vanderbilt University, Nashville, TN, 37235, USA

Fluid momentum has proven to be one of the toughest concepts to grasp in fluid mechanics at Vanderbilt University and other institutions. Understanding the concept of fluid momentum is crucial to understanding and solving many real-world engineering problems. We developed, presented, and evaluated a fluid momentum unit in the Vanderbilt University undergraduate fluid mechanics course during the Fall 2011 semester. This particular course does not have a lab component, however we believe students can benefit from experiments and demonstrations in the classroom. Therefore, we included a hands-on demonstration component. We designed the fluid momentum unit using the Legacy Cycle developed by the Vanderbilt-Northwestern-Harvard/MIT Engineering Research Center (VaNTH ERC). The fluid momentum unit presented in this work achieved some success in helping students understand the concept of fluid momentum and the forces fluids exert on their surroundings. From a quantitative perspective, a statistical significance was not found when comparing the results from the students that received the subject fluid momentum unit and a control group of students that received a traditional lecture-formatted unit. Qualitatively, the subject group applied the conservation of momentum principle effectively in project and exam assessments. Additionally, the subject group student surveys indicated most of the students felt the fluid momentum unit presented in this work helped them learn better compared to traditional lecture units.

I. Introduction

Fluid momentum has proven to be one of the toughest concepts to grasp in fluid mechanics at Vanderbilt University and other institutions.[1,2] Understanding the concept of fluid momentum is crucial to understanding and solving many real-world engineering problems. Undergraduate students as a group have proven themselves when presented with concrete, well-defined exam problems that are similar to problems they have solved in class or in homework assignments. When presented with conceptual exam questions, many of these students have exhibited difficulty. Our hypothesis is by using challenge-based learning along with a hands-on demonstration, students develop a deeper and richer understanding of fluid momentum concepts.

We developed, presented, and evaluated a fluid momentum unit in ME 224 Fluid Mechanics during the Fall 2011 semester. This course is required for all undergraduates in Mechanical Engineering at Vanderbilt University. The course is taught during the student's Junior year. This particular course does not have a lab component, however we believe students can benefit from experiments and demonstrations in the classroom. Therefore, we included a hands-on demonstration component in the unit.

Learning goals for the unit are to understand the concept of fluid momentum and the forces fluids exert on their surroundings. Learning objectives are to apply fluid momentum equations and conceptual understanding to solve fluid mechanics problems. The learning goals and objectives are assessed through group work, written exams, and project reports.

We designed the fluid momentum unit using the Legacy Cycle developed by the Vanderbilt-Northwestern-Harvard/MIT Engineering Research Center (VaNTH ERC).[3] A Legacy Cycle is a way of organizing lessons

*PhD Candidate/Research Assistant, Mechanical Engineering Dept., Mike.Myers@Vanderbilt.edu
†Associate Professor, Mechanical Engineering Dept., Haoxiang.Luo@Vanderbilt.edu

and activities in extended inquiry projects to engage students in a variety of activities that imitate the way scientists approach and solve problems - reading articles, brainstorming with colleagues, designing and carrying out experiments to test hypotheses, conducting campaigns to collect measurements and make observations, interpreting data, and publishing their findings. A Legacy Cycle consists of six stages: Challenge Summary, Generate Ideas, Multiple Perspectives, Research and Revise, Test Your Mettle, and Go Public (Figure 1). The Legacy Cycle has been successful in recent studies.[4,5] Similar alternatives to the traditional lecture format have been explored including active learning[6,7] and integrating design and experimentation.[8,9]

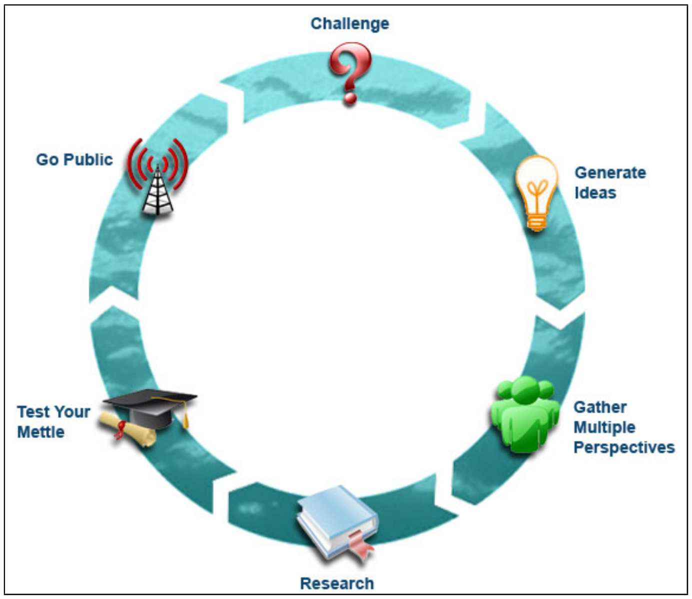


Figure 1. The six stages of the Legacy Cycle.[10]

Unit effectiveness is assessed both quantitatively and qualitatively. Exam scores from similar questions are compared between the Fall 2011 course of 25 students that participated in the subject fluid momentum unit and a control group of ten students from the Spring 2011 Fluid Mechanics course that received a traditional equations-based lecture unit. Quantitative and qualitative results are presented for a pre-unit quiz, a project assignment, and a post-unit survey completed by the Fall students.

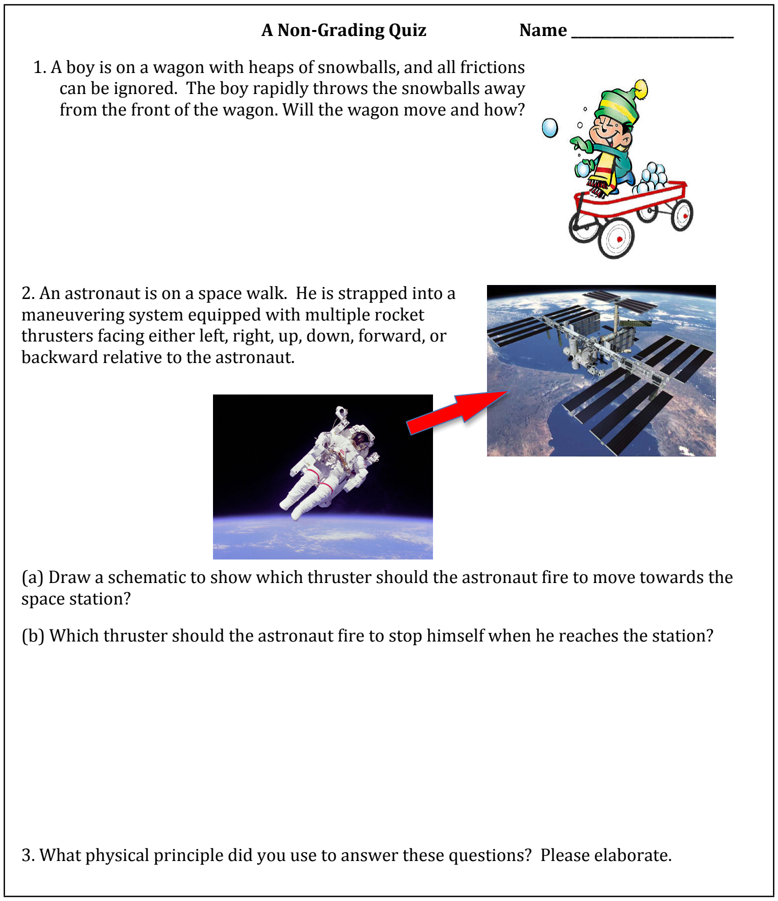
II. Fluid Momentum Unit

The challenge-based fluid momentum unit with hands-on demonstration comprises four-50 minute lectures. The unit incorporates the entire Legacy Cycle. The fluid momentum unit is conducted at about one-third the way through the semester. Prior to the first lecture, a pre-unit quiz (Figure 2 was given to the Fall 2011 students. This quiz is not included in the students' grades and its purpose is to assess the students' fluid momentum knowledge prior to the fluid momentum unit as part of this work.

II.A. Lecture 1

Before presenting any information about fluid momentum, we start with a challenge question to engage the students and bring forth misconceptions. The "Challenge Summary" presents the task that serves to organize and drive activities; it also establishes the expected outcomes that will serve to satisfy the challenge. Having this information in advance motivates students to become fully engaged in the learning process and helps them to discern which information and activities are relevant to the task at hand. The challenge summary for this unit is presented in Figure 3.

A volunteer is solicited to read the challenge question. The students are then asked where the Galápagos Islands are located. This piece is completely unrelated to fluid mechanics and serves to get the students talking and engaged in the lecture. The students are then given three minutes to "Generate Ideas" privately and then all students are encouraged, one-by-one, to contribute one of their ideas to the class. All ideas are


A Non-Grading Quiz **Name** ____________________

1. A boy is on a wagon with heaps of snowballs, and all frictions can be ignored. The boy rapidly throws the snowballs away from the front of the wagon. Will the wagon move and how?

2. An astronaut is on a space walk. He is strapped into a maneuvering system equipped with multiple rocket thrusters facing either left, right, up, down, forward, or backward relative to the astronaut.

(a) Draw a schematic to show which thruster should the astronaut fire to move towards the space station?

(b) Which thruster should the astronaut fire to stop himself when he reaches the station?

3. What physical principle did you use to answer these questions? Please elaborate.

Figure 2. Pre-unit quiz given before the fluid momentum unit.

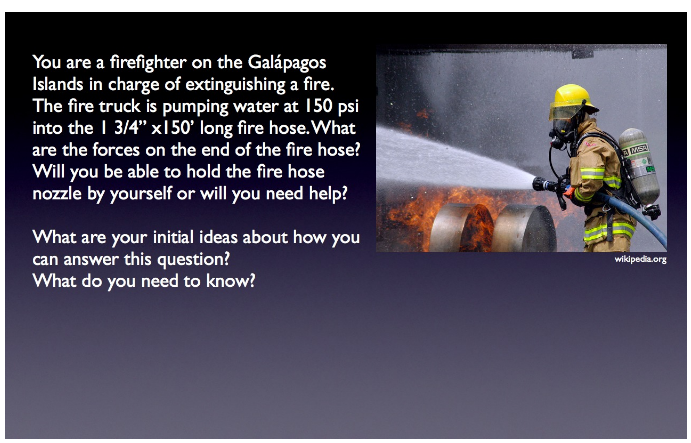


Figure 3. Challenge question to start the fluid momentum unit.

written on the white board or display screen by the instructor. Once all students have had the opportunity to contribute an idea for the board, the entire class is given the opportunity to add any ideas to the board that are not currently there.

The next stage, "Multiple Perspectives", introduces students to resources they can use to answer the questions posed in the previous stage. In the fluid momentum unit, we present three multiple perspectives including the hands-on demonstration. The first comes from a Fire Chief (Figure 4). The second multiple perspective is in the form of a short video clip of a fire hose moving out of control from a firefighter's grasp during a training exercise.[11] The video illustrates the large forces involved and the effect fluid momentum has on a flexible hose. The third multiple perspective is in the form of a hands-on demonstration involving 250 ml squeeze bottles filled with water and with flexible tubing attached to the dispensing tip. Groups of two or three students are given a squeeze bottle with tubing attached and a bucket to catch the water. Each student is encouraged to grasp the squeeze bottle, turn it upside down, and squeeze the bottle to push air through the plastic tubing (Figure 5). The students then turn the bottle right side up and squeeze to push water through the tubing (Figure 6). The students are instructed to record their observations paying close attention to the tubing. Without prompting, the students typically share observations with their group as they are performing the demonstration. The students are then given cellophane tape and thin and stiff wire (e.g. paper clips) and are instructed to form a permanent bend at the end of the tubing, repeat the demonstration, and record their observations.

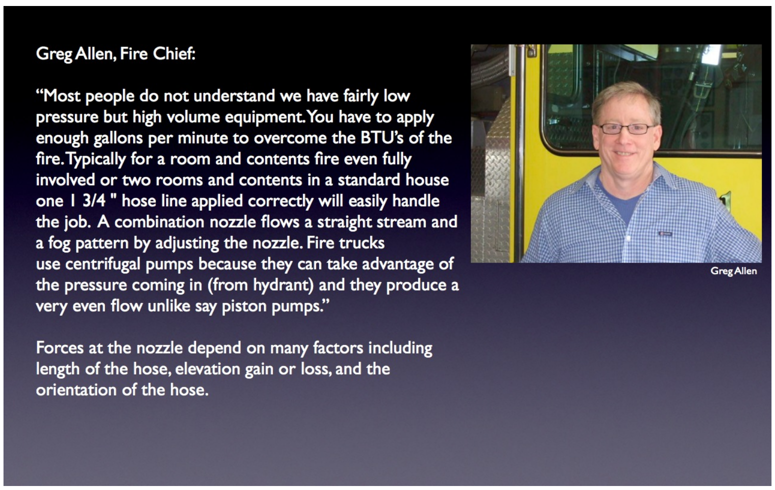


Figure 4. "Multiple Perspectives" from a Fire Chief to help students identify ideas needed to solve the challenge.

The students are encouraged to share their observations with the class and the instructor adds the observations to the white board or screen. At this point, the students are encouraged reflect on the Fire Chief's comments, the video, and the hands-on demonstration to identify other ideas that will help answer the challenge question. These additional ideas are combined with the previous ideas and the group, instructor and students, review the list as a starting point for the "Research and Revise" stage of the Legacy Cycle.

The Research and Revise stage most closely resembles a traditional classroom. This stage starts with a review of the pre-unit quiz (Figure 2) and the lecture concludes with material from the textbook[12] on momentum balance. At the end of the lecture, the students are given the assignment (Figure 7) for the unit which is solving the challenge question presented at the lecture beginning. The assignment adds an extra piece to the problem by asking the students to determine if the water from the fire hose can reach a fire 100 feet above the ground. A rubric (Figure 8) is given to the students to help them in preparing their projects and to assist the grader. The project intentionally leaves many details for the student to define.

II.B. Lecture 2

The "Research and Revise" stage continues in lecture 2 with material from the textbook[12] on control volume, derivation of momentum flux, and an example of fluid flowing from a lab sink faucet. The astronaut problem from the pre-unit quiz is discussed in detail.

Figure 5. Hands-on demonstration with air being pushed through the hose by squeezing the bottle upside down.

Figure 6. Hands-on demonstration with water being pushed through the hose by squeezing the bottle right side up.

ME 224 Fluid Mechanics
Fall 2011

Fluid Momentum Assignment

Problem statement

You are a firefighter on the Galápagos Islands in charge of extinguishing a fire. The fire truck is pumping 150 gallons per minute of water at 150 psi into the 1 ¾" (inner diameter) and 150 feet long fire hose. What are the forces on the end of the fire hose? Will you be able to hold the fire hose nozzle by yourself or will you need help? Will you be able to extinguish a fire that is 100' above ground?

Assignment

Do research and find out the pressure loss of the hose. Consider one or more practical fire-fighting situations and analyze the problem. In addition to meeting the format requirement for the standard homework, your report should include the result from your research and also the practical concerns as you solve the problem.

The following details will help you achieve success with this project:

- Be sure to include all assumptions you make in solving the problem.
- Include all equations you use and identify all principles and laws you use.
- Use metric units.
- You may consult your fellow classmates, Prof. Luo, the TA, and Mike Myers in working through this project. Your textbook and other literature are excellent resources for helping you work through the solution.
- The project report you submit must be your own original work.

Report submission. Submit your completed report in electronic form in OAK. Due Monday, October 17th, 2011.

Figure 7. Project assignment given to the students at the end of the first fluid momentum lecture.

II.C. Lecture 3

The "Research and Revise" stage continues in lecture 2 with material from the textbook.[12] The jet engine thrust example from page 211 (Figure 9) is discussed and the problem is solved interactively with the students. The general form of the momentum equation for any control volume is presented and the students are reminded that all examples thus far in the unit are one-dimensional. A special note is made that the fire hose assignment (Figure 7) involves bends in the hose making it a two-dimensional problem. The impinging jet on a vane example from page ??? (Figure 10) is discussed and then a pipe bend example from page ??? (Figure 11) is presented and analyzed. The discussion highlights the unknown exit velocity and area. The Bernoulli principle is presented as a method to determine the exit velocity and then conservation of mass to get area. The similarity of this problem to the fire hose problem is discussed as both have unknown velocity and area at the exit. One student is given an assignment to give a five-minute presentation to the class during the next lecture. The presentation can cover anything related to fluid mechanics.

II.D. Lecture 4

The final lecture in the fluid momentum unit starts with a repeat of the hands-on demonstration using the squeeze bottles. The idea is the students have a deeper understanding of fluid momentum and will observe and discover behavior they missed during the first demonstration. A simple drawing of the tube is presented illustrating the forces. The student presentation on a fluid mechanics topic of their choice is conducted. The purpose of this presentation is to tap into the diversity of knowledge and backgrounds present in the class, to refine student presentation skills, and to promote a dynamic and engaging classroom. The lecture is concluded with material on moving control volumes. The material includes defining a moving control volume as a control volume with linear acceleration, a discussion on fixed control volumes with simple inlet and outlet, and the general form of the momentum equation. Moving control volume equations are presented and a rocket example is solved with the class.

Your project will be graded using the following rubric:

Outcomes with Criteria		Below Stds	Meets Stds	Exceeds Stds	SCORE
Knowledge/Understanding					
	System accurately represented in multiple formats (illustrations, words, data, equations)	0-2	3-4	5	
	Showed accurate and complete calculations with units	0-2	3-4	5	
	Appropriate control volume described	0-2	3-4	5	
	Fluid momentum concepts accurately represented	0-2	3-4	5	
Reasoning					
	Fluid forces accurately identified	0-5	6-7	8-10	
	Justified which forces and interactions can be neglected	0-5	6-7	8-10	
Skills					
	Accurately employed analysis tools	0-5	6-7	8-10	
	Effectively communicated procedures, analysis, and conclusions	0-7	8-11	12-15	
	Followed rules of grammar, sentence construction, and punctuation; spelling errors minimized	0-1	2-3	4-5	
Products					
	Required analysis presented; all units stated and consistent; all charts have titles and axis labels with units present	0-1	2-3	4-5	
	Analysis accurately approximates the problem	0-5	6-7	8-10	
	Submitted report in proper format	0-1	2-3	4-5	
	Submitted report is well organized and cogent	0-5	6-7	8-10	
					TOTAL (out of 100)

Grading scale
90-100 A
80-89 B
70-79 C
60-69 D
< 60 F

Figure 8. Project rubric given to the students to assist them in preparing their projects and to assist the grader.

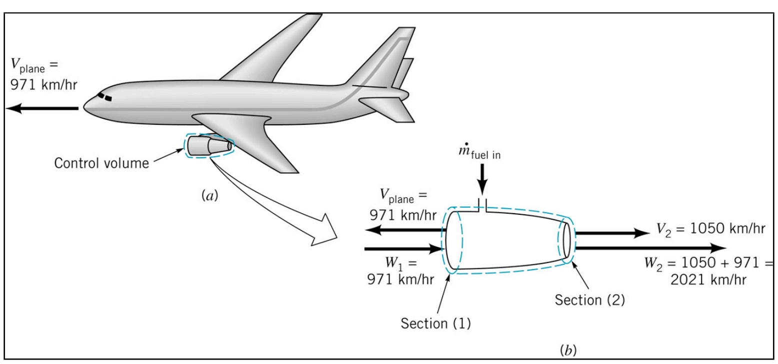


Figure 9. Jet engine thrust example.[12]

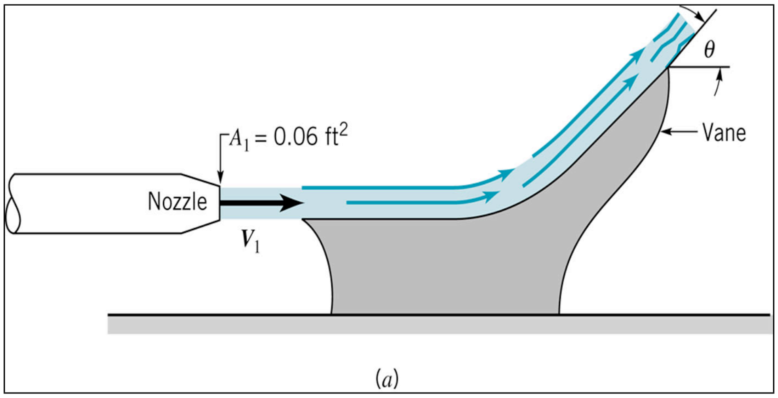


Figure 10. Impinging jet on vane example.[12]

pipe_bend.pdf

Figure 11. Pipe bend example.[12]

II.E. Assessments

Fluid momentum unit assessments include the fire hose project discussed above, a post-unit exam with one fluid momentum question (Figure 12), and a final exam with two fluid momentum questions (Figure 13). The exams constitute the "Test Your Mettle" stage of the Legacy Cycle while the project report represents the "Go Public" stage.

A 30° reducing elbow is shown. The fluid is water with density 1000 kg/m³. The atmospheric pressure is 100 kPa. Determine both the horizontal and vertical anchoring forces needed to hold the elbow in place.

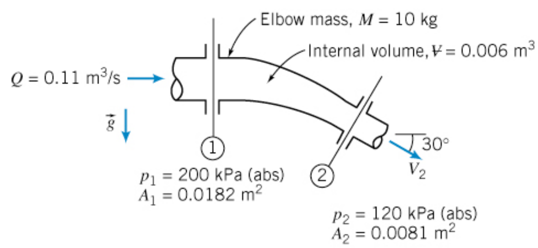


Figure 12. Fall 2011 post-unit exam fluid momentum question.

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Figure 13. Fall 2011 final exam fluid momentum question.

III. Results

Assessing the effectiveness of the subject fluid momentum unit is accomplished quantitatively and qualitatively. The pre-unit quiz described above provides insight into student knowledge and misconceptions prior to the unit. The quiz is an optional component of the fluid momentum unit to be administered when the instructor desires to better understand student knowledge prior to the unit and to facilitate student awareness of their own knowledge. Results from the Fall 2011 pre-unit quiz are summarized in Table 1. Out of 25 students, 22 (88%) completed the pre-unit quiz. Principles identified by students to answer question 3 are summarized in Figure 14. Most students explained movement of the wagon and astronaut using Newton's Laws or Newton's 3rd Law while 18% correctly identified momentum conservation.

	Question 1	Question 2	Question 3	Overall
Average Score	89%	94%	52%	75%
Standard Deviation	30%	22%	38%	27%

Table 1. Pre-unit quiz aggregate scores.

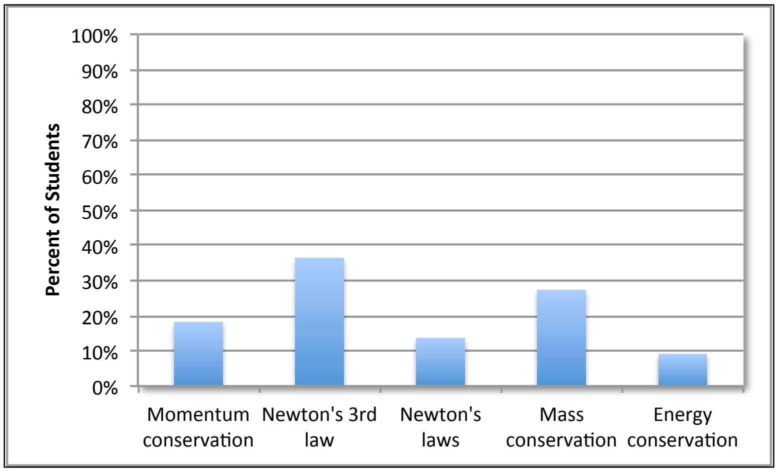


Figure 14. Pre-unit quiz physical principles identified by students to explain movement of the wagon and astronaut. Some students used multiple principles to explain the behavior.

Figure 15 contains the "Generate Ideas" results from the Fall 2011 students. The students identified many ideas and items that need to be considered while working the solution to the firefighter problem. The challenge question and the multiple perspectives did not prompt the students to think of control volume analysis, Bernoulli principle, or conservation of momentum. Ideally, the challenge question and multiple perspectives bring forth all of the items the students need to learn to solve the challenge question and to complete the learning goals for the unit. Thus, at the end of the "Generate Ideas" stage, the students have created a lesson plan for the unit that matches the instructor's prepared lesson plan. Figure 16 contains observations the students shared with the class after the hands-on demonstration.

Weight of hose
Angle of hose
Water velocity
Elevation change
Human/hose friction
Human weight
Hose moving
Water mass flow
Human stance
Water distance after nozzle
Water volume
Length of hose
Air pressure
Area of hose
Pressure * area
Constant area?
Exit diameter
Water density
Exit shape
Force of water at nozzle
Friction in hose
Human strength
Human/ground friction

Figure 15. Student ideas from the "Generate Ideas" stage.

Elbow slows down flow
Higher pressure = higher velocity
Air flow – nothing happens
Flow direction opposite of deflection
Pressure straightens out hose
High velocity = greater deflection
Rate of flow = longer distance

Figure 16. Student observations after the hands-on demonstration.

Figure 17 illustrates the results from the Fall 2011 fire hose project. Out of 25 students, 24 students submitted project reports. Seven areas are identified as critical to solving this and similar problems: Defining a control volume, stating the assumptions, identifying forces that can be neglected, using Bernoulli's principle to obtain nozzle area, using momentum conservation, incorporating a bend in the hose, and using consistent units. Interestingly, only 58% of the students incorporated a bend in the fire hose.

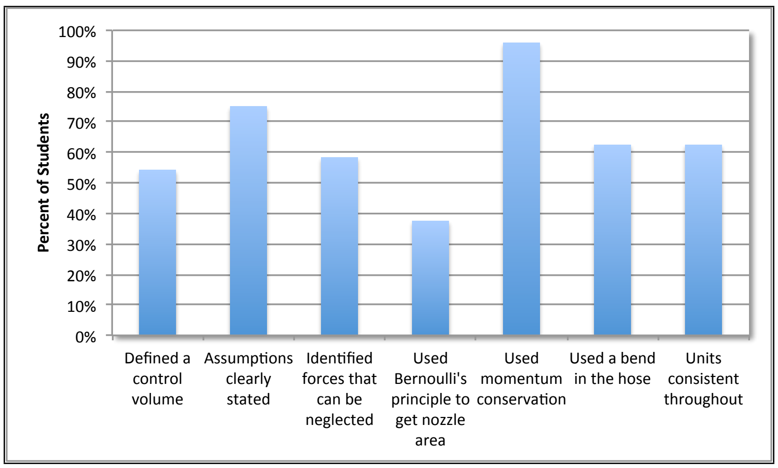


Figure 17. Fire hose project results.

Figure 18 summarizes the results for the post-unit exam fluid momentum question. Out of 25 students, 24 completed the post-unit exam. Six areas are defined as critical to solving this problem: Defining a control volume with coordinate system and forces, stating the assumptions, incorporating pressure forces, including water and elbow weights, using momentum conservation, and using consistent units. While the results indicate a good understanding of when to use momentum conservation, basic problem solving skills such as defining a control volume need to be addressed.

Figure 19 illustrate the results for the Fall 2011 final exam fluid momentum questions. Out of 25 students, ? completed the final exam. ? areas are defines as critical to solving this problem: Defining a control volume with coordinate system and forces, stating the assumptions, ?, ?, using momentum conservation, and using consistent units. The results indicate ??

The Spring 2011 Fluid Mechanics course is used as a control group to facilitate assessing the fluid momentum unit's effectiveness. The Spring 2011 course and the Fall 2011 course were taught by the same instructor. The Spring 2011 final exam contained two fluid momentum questions (Figure 20). Figures 21 and 22 summarize the results from this exam. Six of the ten students answered the astronaut question incorrectly and none of the students incorporated a bend in the hose in the firefighter problem. Table 2 contains a summary of results from the Fall 2011 post-unit exam, the Fall 2011 final exam, and the Spring 2011 final exam. The results are not statistically significant and yield no insight into the effectiveness of the fluid momentum unit detailed in this work.

A post-unit survey (Figure 23) provides a mechanism for student evaluations of their own learning. This instrument is not part of the fluid momentum unit and serves as a qualitative assessment of the unit itself. Results from the Fall 2011 survey are summarized in Figure 24. Of the 25 students in the class, 21

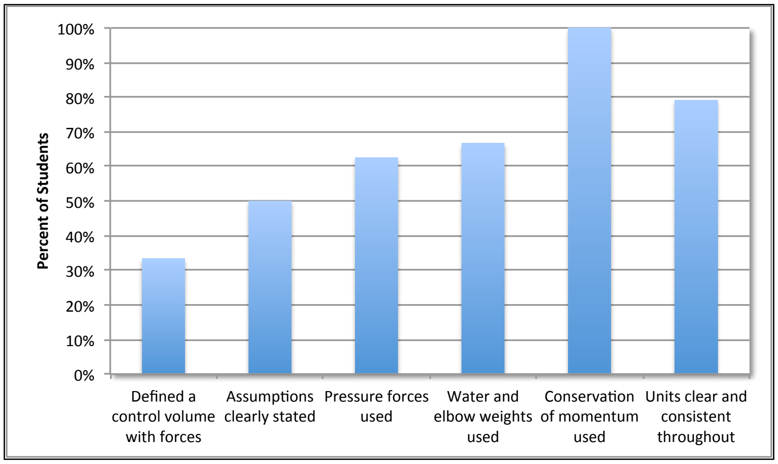


Figure 18. Post-unit exam fluid momentum question results.

final_results.pdf

Figure 19. Fall 2011 final exam fluid momentum question results.

Assessment	Fluid Momentum Questions		Overall	
	Average	Standard Deviation	Average	Standard Deviation
Fall 2011 post-unit exam	78%	16%	84%	12%
Fall 2011 final exam				
Spring 2011 final exam	83%	12%	89%	7%

Table 2. Comparison of aggregate results from Fall 2011 exams with the Spring 2011 final exam.

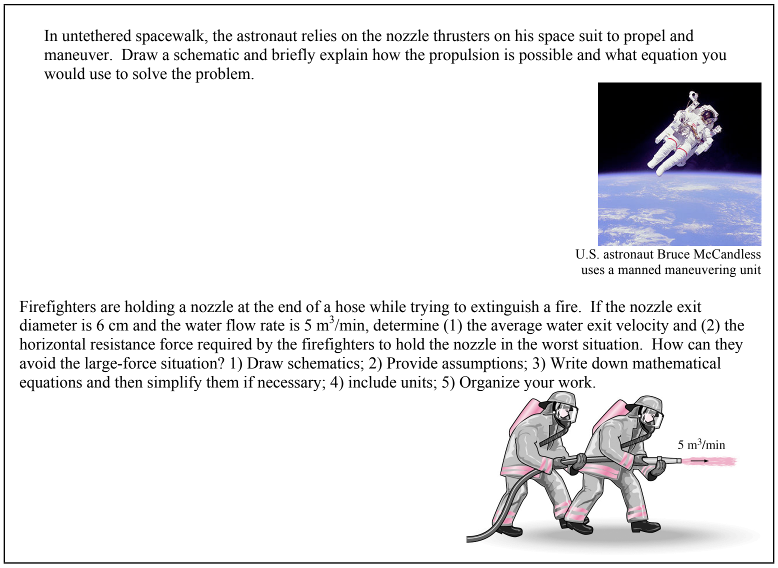


Figure 20. Spring 2011 final exam fluid momentum questions.

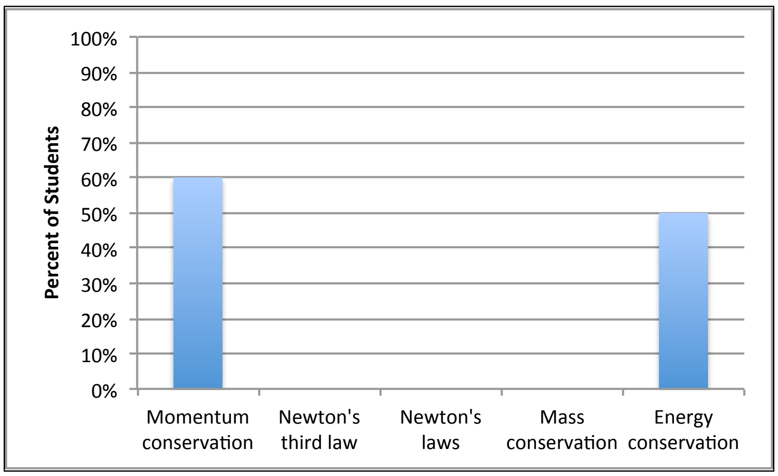


Figure 21. Spring 2011 final exam results from astronaut question.

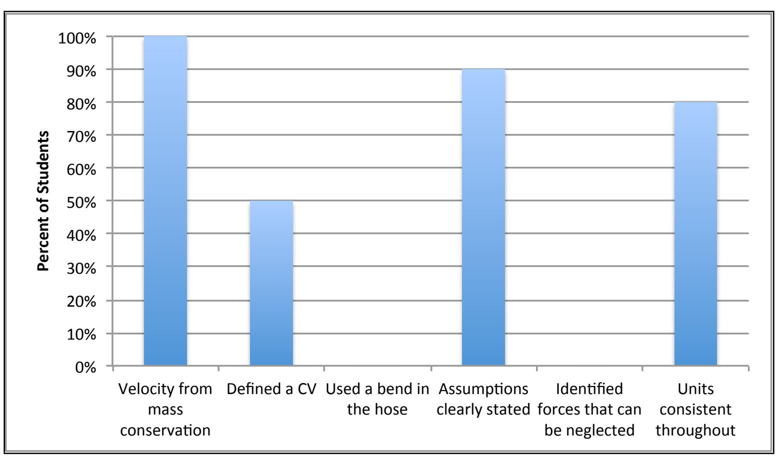
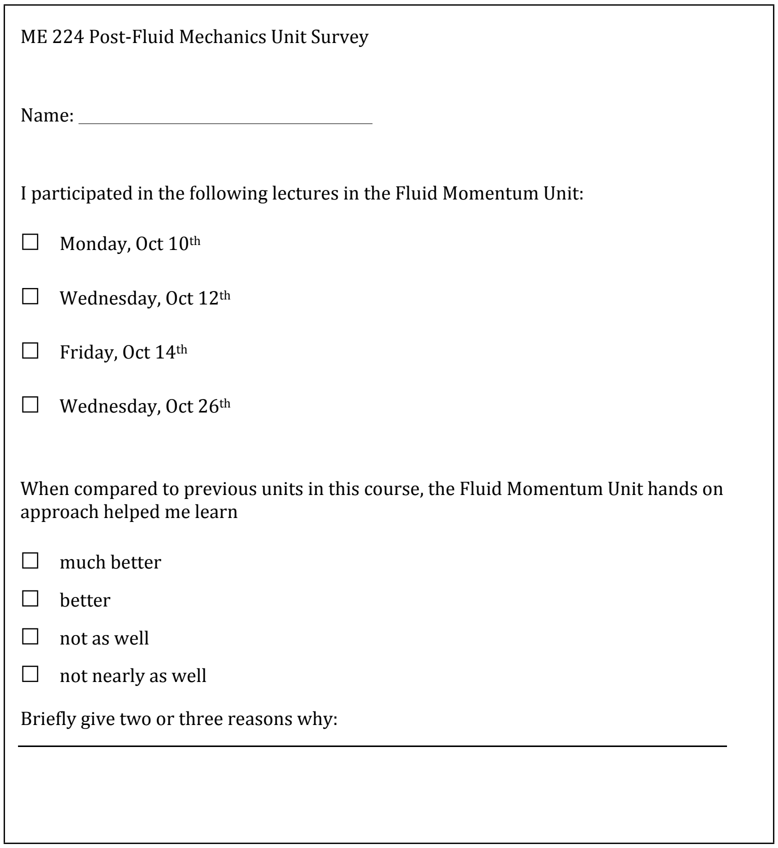


Figure 22. Spring 2011 final exam results from firefighter question.

(84%) completed the survey and 90% of those indicated the fluid momentum unit helped them learn the same or better when compared to previous units in this course. The majority of students felt the hands-on demonstration helped them understand fluid momentum forces.



ME 224 Post-Fluid Mechanics Unit Survey

Name: ______________________________

I participated in the following lectures in the Fluid Momentum Unit:

☐ Monday, Oct 10th

☐ Wednesday, Oct 12th

☐ Friday, Oct 14th

☐ Wednesday, Oct 26th

When compared to previous units in this course, the Fluid Momentum Unit hands on approach helped me learn

☐ much better

☐ better

☐ not as well

☐ not nearly as well

Briefly give two or three reasons why:

Figure 23. Post-unit survey.

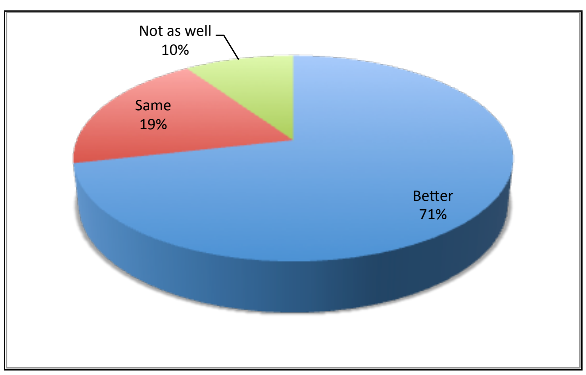


Figure 24. Fall 2011 post-unit survey results to the question "When compared to previous units in this course, the Fluid Momentum Unit hands-on approach helped me learn _______".

IV. Conclusions

The fluid momentum unit presented in this work achieved some success in helping students understand the concept of fluid momentum and the forces fluids exert on their surroundings. From a quantitative perspective, a statistical significance was not found when comparing the results from the students that received the subject fluid momentum unit (the Fall 2011 group) and the students that received a traditional lecture-formatted unit (the Spring 2011 group). Qualitatively, the Fall 2011 group applied the conservation of momentum principle effectively in project and exam assessments. Additionally, the Fall 2011 student surveys indicated most of the students felt the fluid momentum unit presented in this work helped them learn better. Comments from the survey indicate the challenge question involving a real-world firefighter problem engaged the students from the start and helped connect the material as the students were learning. Most students indicated the hands-on demonstration helped them understand fluid momentum forces.

Modifications to the unit presented here could include adding a removable nozzle to the squeeze bottle tube. This modification would allow student comparisons of fluid momentum forces from a bend and from a nozzle. One could also devise a method of measuring the forces on the hose, however this significantly increases the demonstration's complexity. Addition of a "Multiple Perspective" that prompts the students to identify control volume analysis in the "Generate Ideas" stage would benefit student learning.

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