ASTFE
American Society
of Thermal and Fluids Engineers

7th Thermal and Fluids Engineering Conference (TFEC)
May 16-18, 2022
Partially Online Virtual and in Las Vegas Conference

TFEC-2022-40708

INTEGRATION OF COMPUTATIONAL FLUID DYNAMICS INTO AN INTRODUCTORY FLUID MECHANICS COURSE

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ABSTRACT

Traditional didactic collegiate thermal-fluid engineering courses, in particular those without a laboratory component, lack the opportunity for experiential learning, among other beneficial aspects of hands-on learning. The process of conducting experiments and comparing results to theoretical predictions provides invaluable educational experiences, of which include but are not limited to the introspective questioning of established paradigms, the conversion of short-term memories into long-term memory recall through practice, and the ability to be actively engaged in learning through partner or group activities. In an attempt to overcome this deficiency, the use of Computational Fluid Dynamics (CFD) software was integrated into a lecture-based junior-level introductory Fluid Mechanics course. The use of ANSYS CFX, a commercially available CFD software, was used to complement the presentation and instruction of the subject of differential description of fluid motion, namely the Navier-Stokes equations. Students used ANSYS CFX to not only generate visualizations of flow and pressure fields, but also to validate analytic solutions for potential and laminar viscous flows for various geometries, boundary conditions, and fluid properties, after a brief introduction to the theory of the Finite Volume Method. Student perceptions on the use of ANSYS CFX toward their learning and engagement were quantified through mixed-method open- and closed-ended survey questions, which were coded and analyzed to provide qualitative and quantitative feedback. The results of the survey are intended to guide the implementation of CFD into a junior-level mechanical engineering course, with an emphasis on increasing student engagement with the material and satisfaction.

KEY WORDS: engineering education, computational fluid dynamics, fluid mechanics, thermal-fluid education

1. INTRODUCTION

Laboratory components of courses provide students the opportunity to both test theoretical concepts and reinforce the learning being done in the classroom. In chemistry lab, the mixing of two components producing a gas through visible bubbles brings to life a stoichiometric equation they had previously only seen mathematically [1]. A roller coaster in physics class can show students the energy lost due to non-conservative forces in a system [2]. Both experiences show students that concepts within the classroom have application outside the classroom, as well as provide another method for introducing fundamental concepts in a more engaging manner. However, in courses where designing and conducting an experiment can become too costly and time consuming to be deemed beneficial to a university's curriculum, students are missing out on major benefits to their learning. To bridge this gap, and provide students another avenue for learning, educators have turned toward digital software to replicate those missing lab components.

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DOI: http://dx.doi.org/10.1615/TFEC2022.emt.040708

Nesbit describes the need for the finite element method (FEM) to be integrated into the undergraduate engineering curriculum. The first reason discussed is the ever increasing use of FEM in industry. FEM is often used by engineers to not only aid in design of new mechanical components but also validation of the safety in design. Seeing as FEM has become such an integral part in the engineering industry, the better students can understand the intricacies in its use, the more likely they are to use it without error. Additionally, Nesbit mentions the benefit to student understanding the utilization of FEM has. As situations of mechanical stress, fluid flow, heat transfer, etc. become more complex, the harder it is for students to visualize and understand. With the visual aid of FEM, students are not only introduced to the material an additional time, but also able to test their understanding of the fundamental concepts in order to create the model. Similarly, with the expansive capabilities of FEM software, students are able to create and analyze much more complex and realistic situations than they might be able to in a classroom setting [3]. Berselli goes on to explain the actual integration of computer-aided engineering (CAE) software to analyze mechanical devices.

At the University of Genova, for their Design of Automatic Machines course, a project-based learning activity was implemented. In this project, students aimed to progress through five distinct stages of the design process utilizing CAE in every step. First, the students used a PTC Creo Assembly environment to model the complete system, perform motion analysis and optimization, perform dynamic analysis and optimization, perform structural analysis and optimization, and finally use all results to select existing parts for potential manufacturing of the system. Not only does this project allow students to follow a complete design process, similar to what they might see in industry, utilizing a digital modeling software, but it also reinforces concepts they have learned in the classroom with a complex system. Idealized systems are often those that are evaluated in class to teach the basic concepts, but do not allow the students to expand their thinking as much as a more complex, true to life system would. Without limitations of laboratory space or budget for materials, students are able to solidify the basic concepts they learned in class as well as apply their understanding to new situations [4]. In contrast to using software to simulate the purely mechanical, Sert discusses the potential benefits of using computational fluid dynamics (CFD) in undergraduate engineering education.

While CFD has mostly been limited to use in graduate engineering courses and for research purposes, Sert sees a potential benefit to implementing CFD software in undergraduate engineering. The course for which he sees CFD providing the most benefit is fluid dynamics. Due to the complexity of fluid flow, students tend to have a harder time visualizing different scenarios in fluid dynamics than they do scenarios in strictly mechanical scenarios. With a better visualization, students are able to better develop the critical thinking skills that are necessary to understand the more abstract, fundamental concepts of fluid flow. They are able to properly shape their thinking. Additionally, students are not typically able to visualize fluid flow due to the lack of exposure to these scenarios in their everyday lives [5]. Sert agrees with Pines that students are more prone to becoming discouraged when learning basic concepts that are not easily shown in practice and difficult to relate to. Utilizing a tool like a CFD software not only provides students a chance to become excited by what they are learning, but also gives them an advantage over their peers by understanding the concepts of a software commonly used in industry [5, 6]. Widiastuti also sees the advantage of finite element analysis (FEA) software in the instruction of a heat transfer course for undergraduate engineers.

Widiastuti recognizes the need to keep students engaged in the classroom through activities that have an obvious application in the engineering industry while also adhering to pedagogical practices. With the goal of better converting short term exposure of a topic to long term memory, Widiastuti followed the experimental learning cycle. This cycle involves concrete experience, observation and reflection, the formation of abstract concepts, and testing in a new situation. In the reflective observation phase, FEA would be used to show a temperature distribution within a set model. Using visualizations of a temperature distribution, students could compare the FEA results to their own analytic calculations, thus providing them more confidence in their heat transfer problem solving abilities as well as an avenue for abstract conceptualization. While the other portions of the learning cycle do not directly use FEA, they are made possible by the software helping guide students in their learning. This experimental learning cycle using FEA has not yet been implemented, but had positive reactions from the faculty at Widiastuti's university [7].

To the researchers' knowledge, there has been no formal study on student perception of the implementation of a CFD software in an introductory Fluid Mechanics course. Researchers aim to understand not only how CFD affected student learning and understanding of course concepts, but also what aspects of the software's implementation benefited students the most (e.g. visualization of fluid flow or validation of hand calculations). The software the research team will use in this study is ANSYS CFX.

2. METHODOLOGY

The course in which ANSYS CFX was implemented is titled Introduction to Fluid Mechanics. This course is primarily administered to junior-level mechanical engineering majors; however, this course can also be taken by bioengineering majors at nearly any point in their degree program. This course covers hydrostatics, Reynolds Transport Theorem, differential descriptions of fluid flow, including the Navier-Stokes equations, and dimensional analysis. There is currently no laboratory component to this course at the researchers' university.

The students were presented a mixed methods survey of open-ended questions both before and after ANSYS CFX was implemented. The questions were administered to the students via the University's approved platform, Qualtrics. The first survey consisted of yes/no questions inquiring about their familiarity with ANSYS CFX and expectations in utilizing the software. Each question was followed by a qualitative feedback question that allowed the student to elaborate on their previous answer. Table 1 summarizes the questions asked to the students.

Table 1 Pre-survey questions and answer type (Yes/No = Y/N, Open Response = OR).

No.	Question Statement	Answer
1.a)	Have you had previous exposure to Computational Fluid Dynamics (CFD)?	Y/N
1.b)	If so, where, and in what capacity?	OR
2.a)	Where you taught CFD?	Y/N
2.b)	If so, where and how?	OR
3.	What is your perspective on, or how do you feel about, using ANSYS CFX for this course?	OR
4.	What do you expect to be able to do with ANSYS CFX after completing this course?	OR

The use of ANSYS CFX was to provide flow visualization, and served as validation to solutions the students obtained analytically. Once the students began learning the differential description of fluid flow, namely the Navier-Stokes equations, they were introduced to ANSYS CFX. At first, they were provided results files generated using ANSYS CFX, and used ANSYS CFD Post to post-process the results files. These results files contained velocity and pressure fields of various fluid flows, for which students were independently generating stream lines and other kinematic descriptions of fluid flows for. The students were able to compare their solutions to those generated in CFD Post, providing both qualitative and quantitative comparisons.

Once the students were constructing analytic expressions for velocity profiles and shear stress distributions, they were further introduced to ANSYS CFX, as now they were able to control the fluid properties and boundary conditions of the model. The students would then generate the results and post-process the data, comparing the numeric predictions to those they obtained analytically. They would also generate velocity and pressure distributions, and qualitatively describe the flow fields. Using ANSYS CFD Post, they were able to quantitatively compare their analytically predicted velocity profiles and stress distributions to those generated numerically. It is noted the students were not responsible for constructing the necessary mesh files, nor were they responsible for solver control settings. To aid in the use of the software utilities, the students were provided picture-based written instructions, as well as in-class demonstrations, on how to complete the tasks required of them. The students used the university's computing laboratory hardware, both remotely and in person, to complete the CFD-related tasks.

Following the implementation of ANSYS CFX, students were presented with another survey of open-ended questions pertaining to their experience utilizing the software and the knowledge gained from its use. The questions and answer types are presented in Tab. 2. Since the course was an introductory-level course, the emphasis on the use of ANSYS CFX was not on their proficiency with the software, but rather on the student's perceived use of the software and whether it was beneficial to their learning. Results from both surveys were analyzed using a coding scheme as proposed by Creswell [8]. The coding schemes used in the analysis were developed by two researchers after reading all student responses for the survey questions. Student responses for each question were coded independently, and then discussed until final codes were agreed upon, using a third party arbitrator as a tie-breaker when necessary. The percentages of each code category appearing in the student responses were then calculated. It is noted that summing the percentages of each categorical response for a question can exceed 100%, for a response could have multiple applicable codes associated with it.

Table 2 Post-survey questions and answer type (Yes/No = Y/N, Open Response = OR).

No.	Question	Answer
1.a)	Has the ability to visualize fluid flow in ANSYS CFX enhanced your understanding of fluid dynamics?	Y/N
1.b)	If so, how? If not, why	OR
2.a)	Has using ANSYS CFX improved your problem-solving abilities in fluid dynamics?	Y/N
2.b)	If so, how? If not, why?	OR
3.a)	Did you enjoying the ANSYS CFX software?	Y/N
3.b)	If yes, why? If not, why not?	OR
4.a)	Did you like how ANSYS CFX was implemented in the course?	Y/N
4.b)	If yes, why? It no, why not?	OR

3. RESULTS AND DISCUSSION

The average response rate to the pre-survey was 57.3%, indicating a moderate to high level of student engagement with the pre-survey. The first question students were asked in the pre-survey (Question 1.a)) gauged whether or not they had been exposed to computational fluid dynamics in the past. Of the students asked, 93% of the respondents indicated no exposure to CFD, which was an interesting yet unsurprising finding for the researchers. Of the 7% of of students who did indicate exposure to CFD, many were either self taught or described their encounter as being very brief. Since the response to Question 1.a) was so low, i.e. an overwhelming majority of students had no prior exposure to CFD, further quantification of pre-survey Questions 1.b) through Question 2.b) was not made.

As this is the first implementation of ANSYS CFX in this course, it was desired to know how students felt about using ANSYS CFX in the course, as well as what they hoped to be able to accomplish with the software after acquiring experience with it. To gain insight into these topics, the pre-survey contained two additional questions. Question 3 was: "What is your perspective on, or how do you feel, about using ANSYS CFX for this course?" and Question 4 was: "What do you expect to be able to do with ANSYS CFX after completing the course?" These open-ended questions were coded based upon the following schemes, which are shown in Tab. 3.

The categories found in the pre-survey Question 3 are shown in Fig. 1 a). There were a total of 55 student responses, yielding an average response rate of about 57%. It is noted that responses with a positive connotation are highlighted in green, those with no connotation highlighted in yellow, and those with a negative connotation highlighted in red. This scheme will remain consistent for the rest of the coded responses. Even though students have not had exposure to the software, it does not mean they are ignorant to its significance; 15% of respondents recognized that learning this software would provide them a skill set useful in their later careers. Students understanding the impact of learning a widely used software can have on their life after graduation was showcased earlier in Berselli's research. Almost a third of students indicated a strong interest in using the software, and those that did not largely either were neutral to the introduction of the software or expressed concerns of the software being too difficult to learn.

Table 3 Pre-survey coding scheme for pre-survey Question 3 and pre-survey Question 4.

	Category Description	Code
Question 3	Interested	Students are eager to learn how to properly use the software
	Beneficial	Students see the benefits this software will have in future applications
	Unsure	Students are unfamiliar with the software and therefore have no opinion on its implementation
	Open	Students are willing to learn how to use the software, but do not show enthusiasm
	Neutral	Students show no desire to learn but are not against using the software
	Apprehensive	Students are nervous about utilizing the software within the course
Question 4	Technical Skills	Students expect to have an improved understanding of the software and its capabilities
	Model Flow	Students expect to be able to use the software to provide themselves a visual aid
	Calculations	Students expect to be able to computationally solve fluid dynamics problems with the software in an easier or quicker manner
	Application	Students expect to be able to use this software outside the classroom as it applies to a specific project or career
	Unsure	Students are unsure about the capabilities of the software and what they should expect to do with it

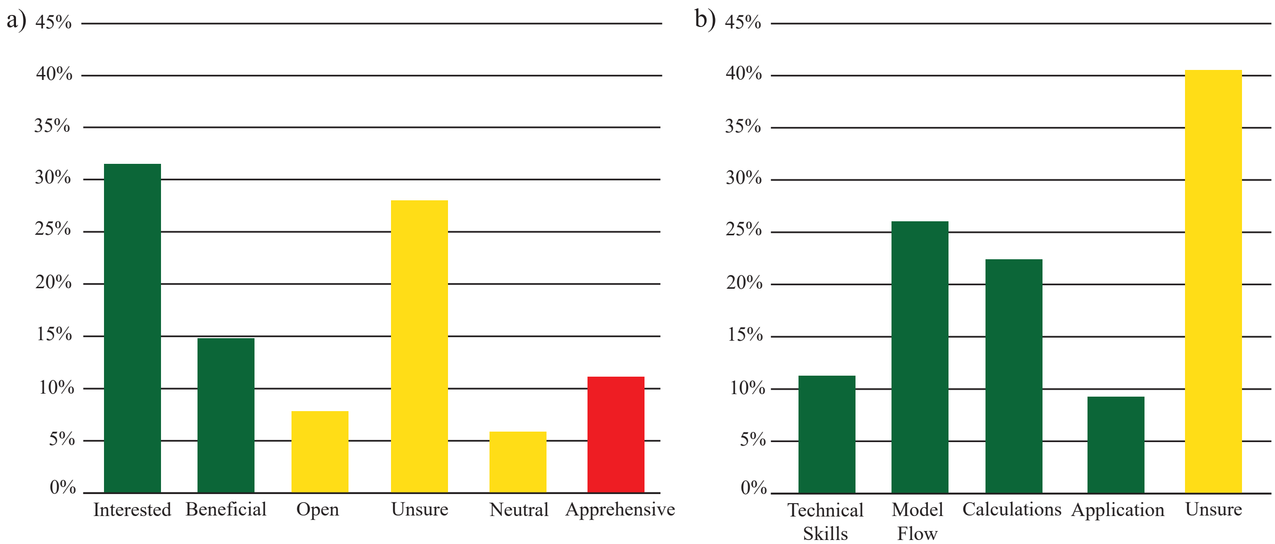

Fig. 1 Categorical response rate for a) pre-survey Question 3 and b) pre-survey Question 4.

The categories found in pre-survey Question 4 are shown in Fig. 1 b). There were a total of 55 student responses, yielding an average response rate of about 57%. When asked what they hope to be able to do with ANSYS CFX after completing the course, a spread of positive responses ranged from being able to apply the software to projects both inside and out of the classroom, to simply gaining a new set of technical skills. As shown by the following student response, some students have a clear direction of their career path and have a desire for knowledge that will help them in their journey: *"Working knowledge to prepare for future CFD courses and experience for being a fluid-thermal analyst in propulsion."* A large amount of students admitted that they did not know what the software was capable of and therefore did not understand what they should be expected to do with it. This is unsurprising considering 93% of students had no previous exposure to the software.

At the end of the term, a post-survey was administered to the students to gain a better understanding of the beneficial and unbeneficial aspects of using ANSYS CFX in the classroom. Question 1 was: "Has the ability to visualize fluid flow in ANSYS CFX enhanced your understanding of fluid dynamics? If so, how? If not, why?" Question 2 was: "Has using ANSYS CFX improved your problem-solving abilities in fluid dynamics? If so, how? If not, why?" Question 3 was: "Did you enjoy using the ANSYS CFX software? If yes, why? If no, why not?" Question 4 was: "Did you like how ANSYS CFX was implemented in the course? If yes, why? If no, why not?" These open-ended questions were coded based upon the following schemes shown in Tab. 4.

Table 4 Coding scheme for post-survey Question 1 through 4.

	Category Description	Code
Question 1	Multiple Conditions	Students appreciate the ability to change multiple conditions within the software and see how the fluid reacts
	Positive	Students indicated a generally positive experience utilizing the software within the course
	Context	Students found that utilizing the software gave them a better understanding of what is actually happening within fluid flow
	Analysis	Students used the software to apply equations introduced in class to produce and/or confirm previous numeric results
	Software	Students did not like using the software due to issues with Virtual Lab; students struggled with understanding how the system was producing a final result
	Did Not Enhance	Students did not find benefit in utilizing the software
Question 2	Confirmation	Students used the software to confirm the answers they got by hand therefore developing confidence in their ability to solve problems by hand
	Expectations	Students understood how fluid flow should behave based on different inputs; students knew, roughly, what solutions to expect from a problem
	Broadened	Students, through using the software, have gained a skill set through that allows them to better realize mistakes within their own work; students mention now having an alternate method to solve fluid flow problems
	Program	Students did not find it necessary to utilize the software within the class; students found the software too confusing for it to be beneficial
Question 3	Practical	Students discuss the future use of the software outside the classroom
	Helpful	Students found the software to be useful within the classroom by providing a visual aid and/or supplementing classroom material
	Fun	Students find the software cool and/or like the fact that learning and using the software breaks up the typical course content
	Neutral	Students did not have a strong positive or negative opinion on the use of the software
	Program	Students were not able to use the software to its fullest extent due to technical difficulties and/or difficulty understanding how to use the software
Question 4	Content	Students felt the use of the software was well aligned with the content being taught in the course
	Time	Students did not feel they had enough time to use the software to its fullest extent; students did not feel they had enough exposure to the software; students wished the software was introduced earlier in the course
	Not Useful	Students did not find the use the software beneficial to their learning

The categories found in Question 1 of the post-survey are shown in Fig. 2 a). There were a total of 69 student responses, giving an average response rate of about 72%. A majority of students indicated the visualization aspect of the software had a positive impact on their understanding. They were able to vary the boundary conditions to see how the fluid reacts. Even just seeing the fluid flow provided students the physical context they needed to better understand what was being taught in the classroom. One student remarked: *"Yes, doing the homework in which we had to analytically solve and then plot the results of a [CFX] simulation vs our analytical curve was very helpful. It gave me a greater ability to predict what sort of velocity profile a given problem should generate, and even while doing it I found that I was able to have a good idea of what the later problems curves would look like before I plotted them."*

As mentioned in Sert's research previously [5], the difficulty in understanding abstract concepts can discourage students, providing context and visual representations remedied this frustration. Of the negative responses received, a good amount of them revolved around difficulties using and access our university's Virtual Lab remote computing platform. This online application allows students to remotely access university computers and the applications therein. Plans to Implement ANSYS CFX in future courses will involve a remedy to this issue.

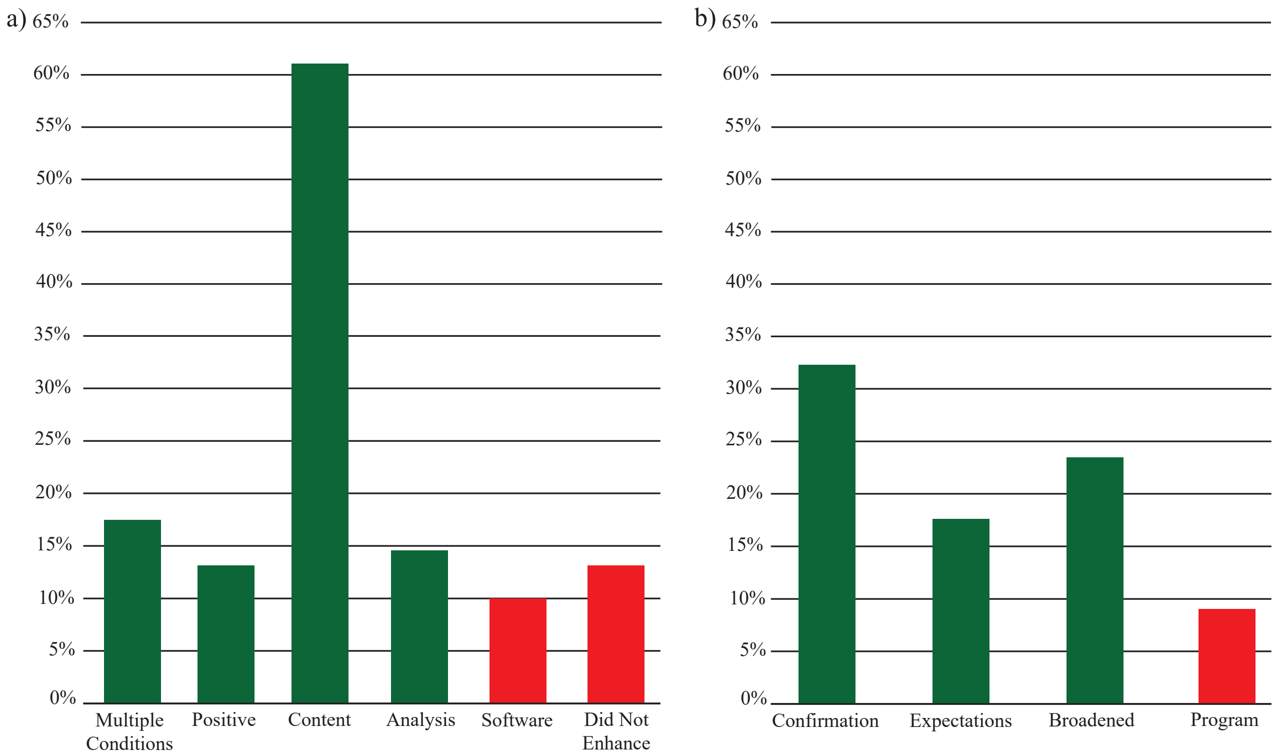

Fig. 2 Categorical response rate for a) post-survey Question 1 and b) post-survey Question 2.

The categories found in Question 2 of the post-survey are shown in Fig. 2 b). There were a total of 68 student responses, giving an average response rate of about 71%. Researchers aimed to see if the use of the software improved student's abilities to problem solve. Many students indicated that solving problems by hand and using ANSYS CFX to verify their results improved their confidence in their problem solving abilities. One student remarked: *"It definitely did help me recognize when I made a mistake in my analytical derivation that may not have been obvious in the math."* It is interesting they made note of this, as they could get the same satisfaction of being correct simply from a solution guide. It is wondered whether the final result coming from ANSYS CFX have more significance in student minds due to their engagement with the software.

Additionally, students began to understand what kinds of answers they should expect of a problem given the situation. This is something a lot of young engineers struggle with, determining what a reasonable answer is. Through using the software and knowing what to expect, students were able to more easily recognize if they had made a mistake somewhere in their work. Respondents also mentioned how by comparing their results to the results in ANSYS CFX, they were typically able to identify where they had made an error. Another student noted: *"It has improved them because I am able to recognize mistakes in my work and correct for them. By graphing the ANSYS results against my expected results from hand calc[ulation]s, I am able to look at both methods and identify the problem."* Alternatively, some students found the program to be difficult to understand. This is an issue researchers see being remedied by spending more time on the theory of CFD as the software is introduced, as well as providing more exposure to the software.

The categories found in Question 3 of the post-survey are shown Fig. 3 a). There were a total of 68 student responses, giving an average response rate of about 71%. Many students enjoyed using the software. Some harped back to the point made earlier that being introduced to a software commonly used in industry brings a practicality to the classroom and they see the direct benefit of what they are learning. One student commented: *"I absolutely did enjoy using the software and am very very happy that it was not only introduced in this class but also had practice problems to supplement it. Not enough courses at Pitt include a real-life component that you can build upon and call a skill. Fluids has given me enough of an intro to ANSYS CFX that I will definitely use it on my own and learn from it for other outside-of-class engineering projects."*

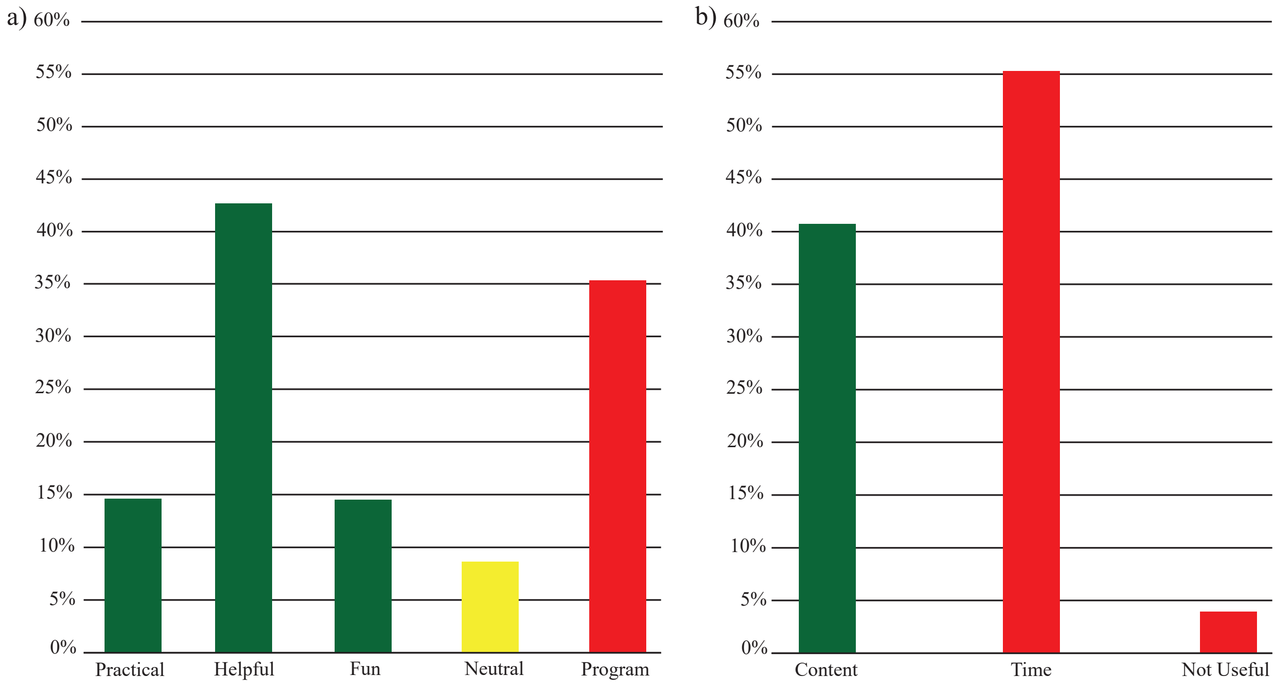

Fig. 3 Categorical response rate for a) post-survey Question 3 and b) post-survey Question 4.

Other students saw a benefit to their education. By having to use the software to re-solve a problem they already solved analytically, they were provided with another opportunity for exposure to the material, as well as an opportunity to visually see the solution. A respondent noted: *"100% Yes it was a little hard to get a handle on at first but even while struggling and making mistakes without I found myself quickly learning which was incredibly rewarding."* Interestingly enough, some students found learning and using the software fun. They felt it broke up the monotony of the classroom. A student commented: *"I enjoyed using it because I feel that I haven't had the chance to use a lot of software in the engineering curriculum that incorporates what we learn in class to real world analysis."* Again, as seen previously, technical issues made the experience of using the software a negative one for many students, and unfortunately hindered both their learning of the software and gaining benefits from its use in the process. Using software to replace hands-on learning does not come without limitations; the cost of licensing and access to the software is the main drawback.

The categories found in Question 4 of the post-survey are shown in Fig. 3 b). There were a total of 68 student responses, giving an average response rate of about 71%. Researchers wanted to assess what was done well in the software's implementation and what was not. While the introduction and instruction of the software was aligned well with course content, there was not enough time spent teaching the theory and software. In terms of alignment, a student commented: *"I did like how it was implemented in this course. It followed along with the homework so it provided a way for you to have a sanity-check for your answers, which also gave reason to do the math behind the problems as well. I think the inclusion of this software was a fantastic choice and would very strongly advocate for it again next year."*

In regards to time spent with the software, another student noted: *"Yes I did. It gave us a nice break and I got to learn something new. It helped me put everything we have learned together. I would not have minded if it* *was used more throughout the whole semester, but obviously there are only so many lectures in a semester to fit it in."* These results give researchers a good direction in terms of restructuring the curriculum to better fit in CFD theory and the application of ANSYS CFX.

4. CONCLUSIONS

Responses indicating that 93% of students had no previous exposure to CFD establishes a need for the theory and software that implement it to be taught. Additionally, students want to learn this software, being excited and open to the possibilities. Those that are nervous about doing so likely have reservations due to their own unawareness of the software and how to use it. After using ANSYS CFX, student perception was largely positive. They were able to contextualize what they were doing. Without everyday exposure to fluid flow, students have little physical reference to what they are learning and that can lead to issues with understanding fundamental concepts. They were better able to problem solve by being able to predict outcomes and determine if they were reasonable, compare solutions to find their mistake, and be confident in their final answer. They know that understanding simulation software will benefit them in their careers as the engineering world has gone largely digital. From the survey, researchers also now understand the need to implement ANSYS CFX sooner, to mitigate problems with the university's Virtual Lab, and to improve overall student understanding of the software through more exposure. In the future, the researchers would like to implement CFD again while objectively and subjectively quantifying how much it appears to benefit student learning.

ACKNOWLEDGMENTS

This work was carried out in accordance to Pitt IRB STUDY21090218. The authors would like to thank David M. Pabst for his assistance in coding student responses.

NOMENCLATURE

Acronyms

CAE	Computer-aided Engineering	FEA	Finite Element Analysis
CFD	Computational Fluid Dynamics	FEM	Finite Element Method

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