EQUIPPING ENGINEERS TO SOLVE COMPUTATIONAL FLUID DYNAMICS PROBLEMS IN SENIOR DESIGN : CHALLENGES AND SUCCESSES USING A COMMERCIAL CFD PACKAGE

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1. ABSTRACT

A growing number of undergraduate engineering programs are currently including courses in computational fluid dynamics (CFD) as part of the elective track. In addition, some programs introduce CFD in the first course in fluid mechanics, while others provide access to the commercial tools in the senior design experience. Here at Cedarville University, we have offered an undergraduate learning experience for CFD that blends these concepts in a unique fashion in both an elective track and a two-semester senior design class. This paper addresses the challenges and successes we have experienced as educators in teaching both the engineering fundamentals and using commercial CFD packages. Over the last four years, we have fine tuned our approach using student feedback and by selectively choosing tools available from CFD literature and software vendors. We have also surveyed our students to improve our teaching methods. In this paper, conclusions from our students are presented regarding the quality of their learning experience, the gaps that exist, and how some of those gaps have/are being closed in the undergraduate education experience in our department.

2. BACKGROUND

Over the last two decades, the growth in the number of undergraduate engineering course offerings in CFD has paralleled the increase in computer power and cost reduction in hardware. Using tools such as Fluent Inc's Flowlab, some engineering programs introduce CFD in fluid mechanics while others provide access to the commercial tools in the senior design experience, see for example (Stern, *et.al.*, 2006). Cedarville University's approach has evolved to offer an undergraduate CFD learning experience that blends both concepts jointly in our elective track and a two semester senior design class. The goal of the paper is to share our applications, yet we do not specifically endorse the commercial code cited over any other code in the marketplace. A large body of reference information can be found in several Internet resources such as cfd-online.com and cfdreview.com/education.

Prior to 2001, Cedarville University did not offer a complete elective track in computational methods. Additionally, after having tried a few packages with our students, we were not 'sold' on one CFD package. The exposure our students had to CFD was exclusively in senior design, a two-semester sequence lasting the entire senior year. In this capstone senior design course, a project team of 4 to 5 students (on average) is given an open-ended design problem that requires the application of a wide range of problem solving skills.

A faculty team discusses and selects all projects. We often get some input from students for project ideas which are generally from their internship experiences. For most projects, students are required to dig deeper and learn new engineering material. For some projects, a CFD analysis is required; in the past, students were largely responsible to self-learn all aspects of the codes using the software representatives as their mentors. Student feedback corroborated that this approach was extremely demanding on their time to both learn and use the software tool, and excessive person hours were used to get up-to-speed with a code and still complete their projects. As our faculty grew, more CFD experience was brought to our department. Beginning in the fall of 2001, we introduced Fluent's CFD software to our undergraduate program. The first set of student CFD learning experiences focused on the two-semester senior design course sequence in mechanical engineering.

3. NEW DIRECTION

Fall 2001, we decided to increase faculty guidance and coaching to enhance student learning in the use of Fluent CFD code. Our focus was to have students work through documentation and simple single phase 2-D/3-D (two/three dimensional) flow tutorials provided with the CFD code. In the earliest learning sessions, we shadowed our students to help them quickly learn the code and to accelerate their progress toward applying CFD tools to their problems. Table 1 lists some of the CFD senior design problems our students have worked on.

In addition to having the students work CFD tutorials prior to their design problems, we had the students gain confidence in the quantitative capabilities of the CFD code. For the convective heat transfer problem, our students were required to compare 1-D hand calculations for laminar and turbulent flow in a heated pipe with 2-D Fluent calculations. For the external flow problems, students were asked to compare laboratory wind tunnel results for standard airfoils to 2-D Fluent calculations. We found that this latter 'validation' exercise was most useful for students to learn to 'weave through' the simplest turbulence models available in Fluent. See Figures 1 and 2 for an example of the validation work required of our students. Figure 1 shows a very important lesson learned – the use of boundary layer meshing – critical for obtaining converged solutions with Fluent that agree closely with experimental wind tunnel results. As outlined in Figure 3, our students use wind tunnel experimentation to compare to their CFD simulation to help design their SuperMileage vehicle body.

Table 1. Examples of Senior Design Problems

Problem Description	Modeling Approach
1. Cooling a Steam Turbine Combustor (commercial)	2-D, Laminar/Turbulent, One Phase, Steady State
2. Simulation of a River Boat for SolarSplash **	3-D, Laminar/Turbulent, Two Phase, Unsteady and Steady State
3. Maneuverable Canards	3-D, Laminar/Turbulent, One Phase, Steady State
4. External Flow over a SuperMileage Vehicle **	3-D, Laminar/Turbulent, One Phase, Steady State
** Student competitions	

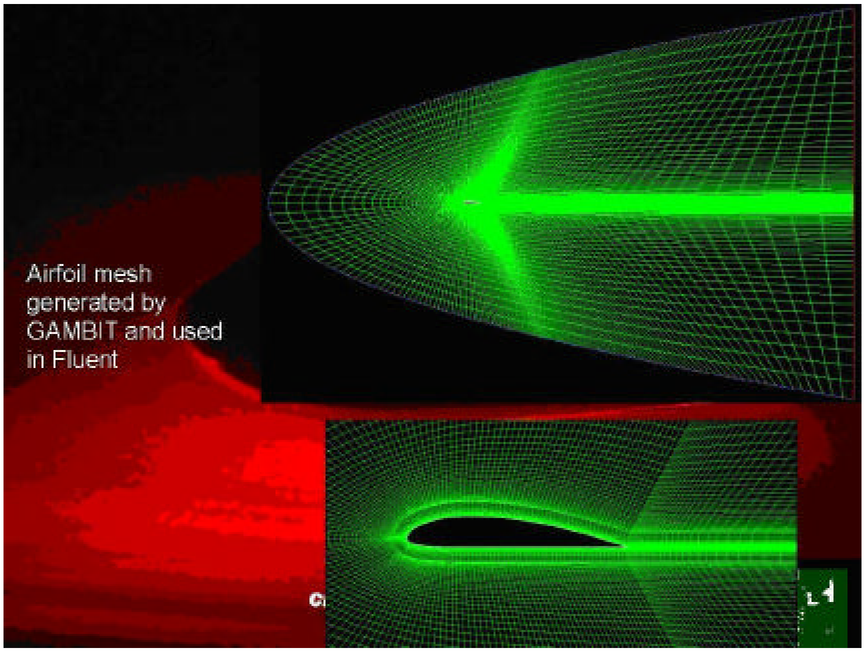

Figure 1. Example of 2-D boundary layer meshing

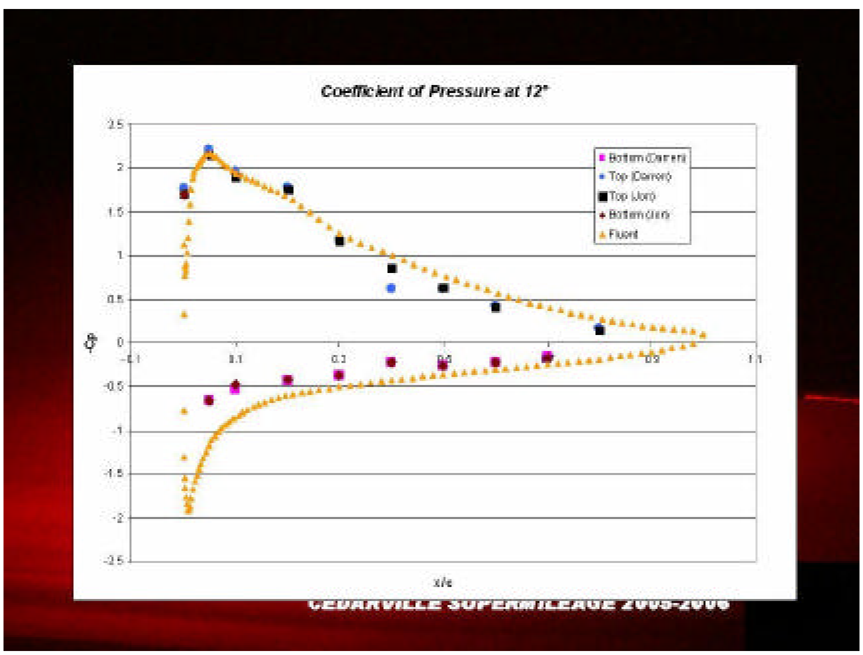

Figure 2. Example of validation of airfoil (N_{Re}= 1.3x10^5)

We learned several important lessons over the last few years which are summarized in Table 2. One of the most important was that two-phase problems were inappropriate at the undergraduate level. Prior to project approval, our faculty were 'split' regarding the appropriateness of giving such a challenging problem to our undergraduate students. As the project proceeded, we found our students having difficulty finding case study documentation and getting 'stuck' in solution initialization and convergence, even with assistance from the software company 'helpdesk'.

Table 2. Key Lessons Learned for Senior Design

Positive Outcomes	Approaches to Avoid
1. For 2-D problems, assign individual design/person	7. Lay entire burden of learning and using CFD code on students
2. For complex 3-D external shape designs, split work CAD/meshing and simulation	8. Assigning 'grad level' problems such as: Transient 3-D, Two Phase
3. Assign validation problem(s) to every senior design student using CFD	9. Ignoring fundamental knowledge of governing equations and mathematical models/methods used in CFD code
4. Offer more in-depth study of underlying CFD principles : course elective track Use computer laboratory classroom to combine lecture and lab experience	10. Underestimating the workload a student has to complete their CFD project
5. Take advantage of vendor resources to build knowledge level of students	11. Allowing students in senior design to go through the senior design year without careful accountability via using GANTT charting of their work
6. For external flow problems, make use of wind tunnel experimentation to validate CFD analysis and turbulence models	12. Complex problems where faculty have no CFD/practical experience to guide students

As educators, it is not difficult to develop a CFD course/track that overwhelms the average engineering student. We wrestled with this issue and concluded that the serious students interested in CFD would take our elective track to gain more in-depth knowledge. The senior design students working on CFD would learn to use the tool via heuristic reasoning from code documentation and faculty guidance, with in-depth training of fundamentals provided by the elective track.

Our CFD elective track focuses on the mathematical methods behind finite difference, finite volume methods, and meshing fundamentals. We cover advanced discussion of the microscopic conservation balances – extensions of their fluid mechanics and heat transfer core courses, using several of the excellent texts available today , see (Anderson, *et.al.*, 1997; Anderson, 1995; Malalasekera and Versteeg 1996; Majumdar, 2005). These books are put on reserve for students to reference. In addition, mesh optimization and solution strategies are introduced.

After initially teaching the sequence, we realized that a strong foundation in turbulent flow modeling was essential for our students. So, our current elective sequence dedicates approximately one quarter of lecture/lab time to teaching turbulence, using CFD code documentation and an excellent reference text, see (Davidson, 2004). Our goal is to prepare students with a good background necessary for the workplace as well as graduate studies.

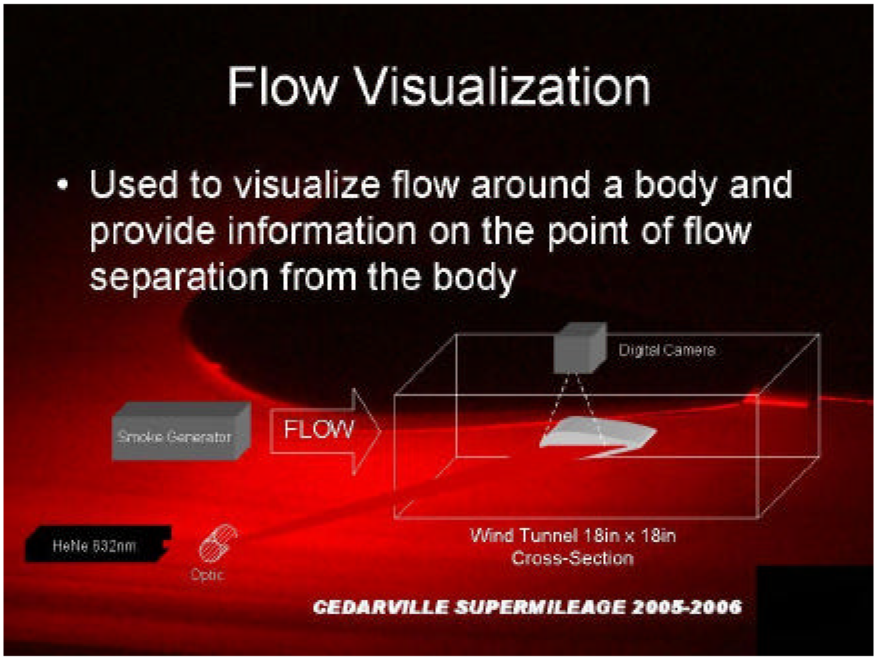

Figure 3. Schematic of wind tunnel experimentation

The most recent change to teaching CFD in our department has been the introduction of Fluent's Flowizard tool. This software greatly reduces the time to solve a specific class of problems through automated mesh generation and simulation. One of Flowizard's useful features is the automatic generation of mesh/Gambit files and simulation/Fluent files.

In addition, Flowizard imports mostly all the 3-D CAD drawings and 'repairs' the geometry during import. This is necessary for proper, coherent meshing. We have found this tool important for students in the senior design experience. Our logic is for our students to learn first the basics of Gambit and Fluent using simple 2-D/3-D tutorials, and to learn Flowizard later. Although limited in capability, Flowizard allows the user to select a reasonably wide range of 3-D CFD design problems that can be solved by undergraduates. Some calculations not available in Flowizard can be accessed using Fluent, because Flowizard generates Fluent files. As the versions of Flowizard (and comparable software offerings by other vendors) mature in capability, the authors see even wider application in undergraduate education as well as industry.

3.1. Student Feedback

Early in this process, most of our feedback came from conversations with our students, our observations, and comments we would read in standardized student evaluations conducted for the elective track courses. The student feedback is summarized in Table 3. The positive aspects of learning CFD include a reasonably useful documentation and tutorial library. Ease of learning diminishes whenever documentation lacks clarity and comprehensiveness, or whenever error messages are not explained which leaves the user in a trial-by-error approach. Existing gaps are identified by double asterisks (**).

3.2 Closing the Gaps

The major issue regarding closing the gaps identified in Table 3 is the in-depth laboratory experiences in the elective track. One difficulty we run into is that some seniors take the computational elective track simultaneous with senior design. These students 'come around' in closing the fundamentals knowledge gap. Another issue is the textbook gap, which we feel is closing but still present. Improvements in CFD code documentation and examples would help new users to solve more complex problems. Although it is difficult to predict questions from every user, the authors feel the software vendor documentation improvements would be most helpful to the educational community.

Beginning this year, a special survey, shown in Table 4, was given to a senior design team of four students who are using CFD to help design a low drag body for the Supermileage competition. The purpose of this survey was to more thoroughly access feedback from students. This recent student group has had the benefit of all the improvements made by the CFD code vendor. We found these students feeling more comfortable with using Fluent, as the Flowizard tool allowed them to more confidently progress on their 3-D simulation and design without the large concern regarding meshing and solution strategies. They noted that having a good starting point with the Fluent and Gambit files automatically generated by Flowizard, they could dig deeper to research how to improve the accuracy of the simulation, including boundary layer meshing issues.

Lastly, there are some success stories regarding how our graduates are using CFD in their professional careers. Several of our students have found jobs specifically due to their exposure and knowledge of using Fluent CFD code. One most interesting example is our graduate who completed his degree in 2001, before we embarked on our 'new direction'. This individual recently visited our campus to speak about the last five years of his career, where he has been performing CFD analyses full-time for a local consulting firm. Our graduate expressed he is using the same CFD code vendor that we adopted and learned the code himself with help from a Ph.D. colleague at his company and the use of the vendor's helpdesk. Most surprising is his expertise in using the software tools without a thorough knowledge of computational methods and turbulence. This individual shared his wish that he would have desired to close that knowledge gap while at Cedarville University.

Table 3. Student Feedback Summary:

CFD Tools: Positive Features

MESHING TOOL

- Visual interface
- Helpful tutorials and Default settings
- The tutorial provides enough information to get started in meshing

SIMULATION TOOL

- The documentation provides a useful starting point
- Visual displays
- The order of how to do things stays the same

AUTOMATED MESHING/SIMULATION TOOL

- Takes you through the process step-by-step
- Assumes default settings for you if you don't know what to use.
- Easy to display/examine results
- Don't need to understand lots of terminology
- Very easy to learn and follow the directions

CFD Tools: Areas of Difficulty OR Needing Improvement

MESHING TOOL

- More complete documentation on how to generate a 'good mesh', with more examples **
- Error messages are vague and confusing**
- Explaining common mistakes or what to avoid**
- Make using GAMBIT more intuitive like CAD programs we use
- Make using boundary layer meshes in 3-D easier
- Make Joining/connecting planes or solids easier

SIMULATION TOOL

- Necessary setup steps are scattered under many different menus; hard to remember all of them
- The tutorial can be too complex for initial learning**
- Provide a simpler tutorial that helps the user understand which settings are the basic must use settings**

AUTOMATED MESHING/SIMULATION TOOL

- Needs to put in an explanation of the calculation accuracy**
- Like to see options available so that a knowledgeable user can override some of the automatic settings
- More flexibility

** Gaps closed by offering the two sequence elective track in computational methods

Table 4. Student Survey Given to a Senior Design Team

SURVEY of Fluent CFD Software Tools

1. List up to five aspects of Gambit that are MOST user friendly when it comes to learning the software:
2. List up to five aspects of Gambit that NEED IMPROVEMENT when it comes to learning the software:
3. List up to five aspects of Fluent that are MOST user friendly when it comes to learning the software:
4. List up to five aspects of Fluent that NEED IMPROVEMENT when it comes to learning the software:
5. List up to five aspects of Flowizard that are MOST user friendly when it comes to learning the software:
6. List up to five aspects of Flowizard that NEED IMPROVEMENT when it comes to learning the software:

Comment on the following regarding Using Fluent
Scores: 1 Needs Improvement 2 Adequate 3 Excellent

7. The OVERALL Documentation of Gambit, including HELP, is _____ comment:
8. The Step by step Details in Gambit Tutorials, including HELP, are _____ comment:
9. The OVERALL Documentation of Fluent, including HELP, is _____ comment:
10. The Step by step Details in Fluent Tutorials, including HELP, is _____ comment:
11. The OVERALL Documentation of Flowizard, including HELP, is _____ comment:
12. The Step by step Details in Flowizard Tutorials, including HELP, are _____ comment:

Briefly Comment on your Understanding of:

13. How calculations are performed
14. How simulation models are selected
15. What would you like to see changed (Gambit, Fluent, Flowizard)?

4. Advancing the Learning Process

Teaching CFD to undergraduates involves training in the use of software tools. More important, however, is to teach the underlying fluid mechanics and transport phenomena. We want our students to be comfortable with understanding how to define boundary (and initial) conditions for a broad variety of engineering problems. In our two elective sequence, we have incorporated analysis of one and two-dimensional problems that have analytical solutions to help our students learn this aspect. We focus our students to 'test' the approximate numerical CFD solutions against exact solutions. One important caveat of our elective track is that we attract students most comfortable with mathematics and computer programming. Our next goal is to incorporate CFD is a broader scope of our undergraduate program, which is more of a challenge.

5. CONCLUSIONS

The role of CFD is ever expanding in the engineering curricula, once relegated to graduate studies. We conclude that the undergraduate CFD training provides a good foundation for future careers in industry and academia, and that this emphasis will only grow larger as the gaps discussed begin to close. We have found from first hand experience that the best mode to introduce and teach CFD to undergraduates is with a special elective track. Our graduates demonstrate good lifetime learning, and incorporating the CFD track has further strengthened this outcome. We continue to enjoy seeing the empowerment of our graduates in the area of computational engineering which brings them joy and insight into our 'created' world.

6. ACKNOWLEDGEMENT

The authors wish to acknowledge the significant efforts by our Supermileage senior design student team. The seniors who were responsible for the CFD and wind tunnel descriptions/results shown in this paper are Joanna Hinks, Darren Holland, Joseph Miller and Andrew Borton. The authors also thank the many past students who have given us feedback about our teaching approaches.

6. REFERENCES

Anderson, D. A., Tannehill, J. C., and Pletcher, R. H. (1997). *Computational Fluid Mechanics and Heat Transfer*, Taylor & Francis, New York.

Anderson, J.D. (1995). *Computational Fluid Dynamics: The Basics with Applications*, McGraw Hill, New York.

Davidson, P.A. (2004). *Turbulence, An Introduction for Scientists and Engineers*. Oxford University Press, Oxford.

Malalasekera, W., and Versteeg, H.K. (1996). *An Introduction to Computational Fluid Dynamics*, Addison Wesley, Boston.

Majumdar, P. (2005). *Computational Methods for Heat and Mass Transfer*, Taylor & Francis, New York.

Stern, F., Xing, T., Yarbrough, D. B., Rothmayer, A., Rajagopalan, G., Smith, S., Otta, S.O., Caughey, D.,Bhaskaran, R., Hutchings, B., Moeykens, S. (2006). Hand-On CFD Educational Interface for Engineering Courses and Laboratories. *Journal of Engineering Education*, **95**, (1), 63-80.