MULTILEVEL IMPLEMENTATION OF FLOWLAB IN ENGINEERING FLUIDS

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Abstract

Historically, introduction of computational fluid dynamics (CFD) in the engineering curriculum has been isolated to graduate level CFD courses. With the development of FlowLab, an educational CFD tool from Fluent, an opportunity now exists for making wider use of the power of CFD within the curriculum and enhancing the students' learning experience with respect to fluid dynamics. The following study reports on the implementation of FlowLab in an undergraduate fluid mechanics course and a graduate viscous flow course in the Mechanical & Aerospace Engineering Department at West Virginia University. The intended goals are to use FlowLab as both an introduction to CFD and as a virtual fluids laboratory to reinforce lecture material from the classroom. Details will be provided on the implementation methodology, materials used, and the student reactions. The authors will speculate on whether the fluids curriculum was enhanced by the addition of FlowLab and the potential future of this tool.

Introduction

In the last decade, many new computational tools have matured to the point of finding common use in the engineering community. One such tool is CFD – Computational Fluid Dynamics – which has gone from primarily a research tool to a highly used design and analysis tool in a multitude of engineering disciplines. With CFD finding such wide use in the engineering community, it is a topic that should be present in the engineering curriculum. Although there is some debate as to the appropriate time to introduce students to the CFD concept, there is broad acceptance that it is an essential engineering topic. Historically, CFD was limited to graduate-level courses, but now some engineering departments have CFD as a senior technical elective. Less common, however, is including CFD in the curriculum at the sophomore or junior level, such as in an introductory-level fluid mechanics class.

The optimal approach for integrating CFD into undergraduate engineering curricula has been investigated in recent studies. At the University of Virginia, a lecture based undergraduate Heat Transfer course was modified to include a two-hour, hands-on computer laboratory.[1] Because limited time was available for learning a complex user interface, specialized teaching modules were developed with the focus on ease of use and fundamental concepts. Similarly, at the Mechanical and Aerospace Engineering department at Utah State University, CFD was integrated into a junior-level fluid mechanics course using an internally developed, student-friendly CFD solver. The in-house solver was designed by Utah State faculty to provide a structured learning experience.[2]

There are cases where a generalized CFD solver has been employed at the undergraduate level. For example, at Kettering University, a course in compressible flow open to undergraduate students has been taught using generalized CFD packages.[3] The compressible flow course was divided into a lecture portion and a laboratory portion, with lectures focusing on theory, while the laboratory portion allowed students to run generalized CFD packages and interpret results. The generalized CFD packages employed were LTCP (an axisymmetric code used by NASA) and ROYA (a software package developed by H. K. Navaz). In a similar case, the commercial CFD package FIDAP was used as an instructional tool in three undergraduate engineering courses.[4] The generalized CFD package allowed students to investigate complex flow fields and gain a better understanding of the governing equations, but it was also concluded that teaching CFD through use of a generalized software interface was not an easy task.

To address the difficulties associated with introducing CFD into introductory or intermediate level thermal-fluids classes, Fluent Inc. developed the student-friendly CFD package, FlowLab. This software was specifically designed so the student could perform flow simulations without in-depth knowledge of CFD. Although FlowLab runs the FLUENT CFD solver and the GAMBIT preprocessor in the background, the easy-to-use graphical interface and the pre-made flow templates offer students the opportunity to use CFD to solve various fluid mechanics problems and use the powerful visualization inherent in CFD to gain further insight into the physics of the flow.

Since its introduction in 2002, FlowLab has been successfully employed in both undergraduate and graduate level curricula, including both lecture-based and laboratory classes.[5] It has been observed that FlowLab can be incorporated very easily into a course without requiring a large start-up time or taking valuable lecture time. Educators have also noted that FlowLab-based CFD problems are a natural complement to lecture material, which typically discusses theory or develops analytical solutions to flow and heat transfer problems.

Under National Science Foundation (NSF) funding, FlowLab-based CFD exercises have recently been developed and applied in the classroom by a consortium of universities, comprised of the University of Iowa, Iowa State University, Cornell University, and Howard University. The focus of the work included customizing the FlowLab interface, which resulted in the NSF Educational Interface.[6,7,8] In comparison with the FlowLab-based CFD exercises in broad use since 2002, the NSF Educational Interface provides greater depth in terms of level of features and modeling options available to the student. Because the CFD exercises developed with the NSF Educational Interface were recently completed in 2005, they have not yet been widely adopted in university curricula. Therefore, there still exists some question as to whether the additional features and complexity offered by the NSF Learning Interface detracts from or provides benefit for the educational experience gained by engineering students using FlowLab in the classroom or lab, especially at the introductory level with sophomore and junior students.

Consistent with the broader acceptance of CFD in undergraduate engineering curricula is the adoption of FlowLab by three recently released textbooks. A textbook by Yunus Çengel and John Cimbala; *Fluid Mechanics: Fundamentals and Applications*, published by McGraw-Hill Higher Education, released in late 2004.[9] Separately, a textbook by Bruce Munson, Donald Young, and Ted Okiishi; *Fundamentals of Fluid Mechanics*, published by John Wiley & Sons, Inc., was released in early 2005.[10] The third book, *Fluid Mechanics for Chemical Engineers*, by James Wilkes, was published by Prentice Hall in late 2005.[11] In choosing FlowLab to serve as a book companion versus a generalized CFD solver, the authors of these books have opted to introduce the subject of CFD to engineers in introductory-level fluid mechanics classes, while shielding the students from the complexity and pitfalls associated with generalized software packages.

The current work documents the implementation of FlowLab exercises in multiple engineering fluids courses at West

Virginia University: an undergraduate fluid mechanics course and a graduate viscous flow course. The exercises employed at West Virginia University were originally released in 2002 by Fluent Inc., although their form has evolved since that date through collaboration with and feedback gained from engineering educators. The objectives for integrating FlowLab into the curricula include a basic introduction to CFD and/or use of FlowLab as a virtual fluids laboratory. The students have the potential to gain a fuller understanding of fluid mechanics on several levels: 1) an introduction to CFD and an appreciation for the need, 2) flow simulations can augment the lecture on specific topics, 3) the visualization component of CFD can provide the student with a stronger understanding of complex phenomena, and 4) if the students are given the opportunity to "pull levers and turn knobs", they will likely have a stronger grasp of parametric effects in fluids and achieve enhanced retention of the material.

FlowLab Material

FlowLab is a virtual laboratory that facilitates the running of predefined fluid mechanics problems under a common interface. FlowLab is not a generalized CFD package. Rather, this software directs the learning of fluid mechanics through an interface which is structured to control the process in which a problem is setup, converged, and post-processed. Using FlowLab, a student may visualize complex flow fields in a virtual environment.

FlowLab has been integrated into the pre- and post-processor GAMBIT, and relies upon the general solver FLUENT for numerical solution. Geometric dimensions, material properties of the fluid, and boundary conditions can be varied by the user. Relevant reports, X-Y plots, contour plots, and vector diagrams can be displayed after the solution is converged. FlowLab uses a PDF reader for viewing documentation and a plot utility for generating X-Y plots. The FlowLab user interface is presented in Figure 1.

A student is guided through the process of setting up, converging, and post-processing the flow problem by the operation menu, which is located in the top-right area of the user interface. Individual tools within the operation menu are summarized below in the order that they appear (from left to right) in the toolbar.

- Geometry: Create and define the geometry model
- Physics: Specify physical models, boundary conditions, and material properties
- Mesh: Create and refine the mesh
- Solve: Start a CFD solver run
- Reports: Analyze the results, reports, integral values, and X-Y plots
- Post-processing: Create contour plots, vector plots, particle tracks, and iso-surfaces representing the flow solution

As the user actuates individual tools in the operations menu, various forms appear in a wizard-like fashion. Through these forms, the user may either accept default settings or specify new input values for parameters such as geometric dimensions, boundary condition values, or convergence criteria, as examples.

The primary advantage of using FlowLab in the classroom is that it is interactive. For each FlowLab exercise, a student may setup and conduct a CFD run from start to finish through an easy-to-use, structured interface. Pages of instructions are not required for each exercise. Each problem contains one or more variables that may be adjusted by a student to assess impact of the parameter upon the final flow solution. From this perspective, each exercise is synonymous with a physical experiment – students gather data from the CFD run, plot and identify trends in the data, and learn something about CFD and fluid mechanics.

Implementation

The goal of implementing FlowLab in the undergraduate fluid mechanics course was primarily to provide the students with a virtual

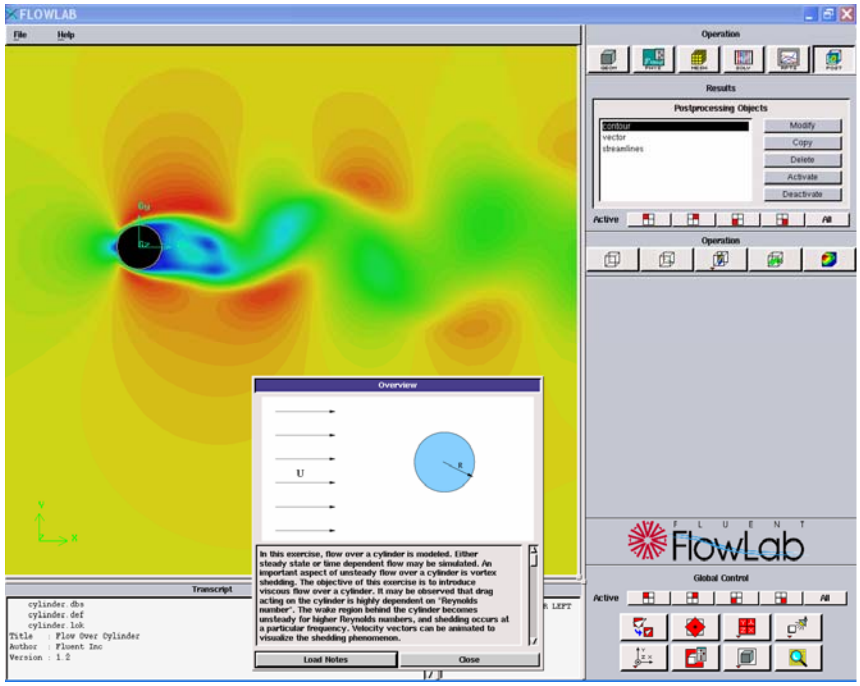

Figure 1. FlowLab Interface.

fluids laboratory to conduct experiments. The introduction of CFD to the students was ancillary in this application, though the use of FlowLab in this type of class can act as a basic introduction.

In a perfect world, engineering departments would have the ability to fit laboratory classes in the curriculum for all appropriate courses. The students would have the opportunity to get hands-on experience in a specific engineering field and apply what they have covered in lecture. However, this utopia does not currently exist and engineering departments have to select which relevant courses have an attached laboratory section and which ones do not; fluid mechanics at West Virginia University is one of the engineering courses that do not have a corresponding lab class. The authors believe that a tool such as FlowLab can help to fill the gap of missing experimental fluids courses. The hope is that the students will then have a better understanding of the lecture material along with improved retention.

FlowLab was introduced during the spring and fall semesters of 2005 to two undergraduate classes and one graduate class. Each class worked on a different problem, though the main pillars of the projects were the same. In both the undergraduate and the graduate level, this was the first course for most students where CFD was introduced. Because the graduate level students had a previous background on fluid mechanics, the outcome of the graduate level implementation was somewhat different than the undergraduate ones.

FlowLab Exercise

1. <u>Undergraduate - Spring 2005</u>

For this initial trial, one FlowLab pipe flow problem was selected from Chapter 8 of Munson, Young, and Okiishi.[10] A tutorial on FlowLab was provided to the students during one of the normal lecture periods; the tutorial material was also made available on-line for later reference. The students had approximately two weeks to conduct the FlowLab study and write a subsequent project report for submission. The components of the FlowLab project are outlined below.

Problem Statement

Conduct a parametric study for fully developed pipe flow by making use of the pipe_fd FlowLab template. Set the pipe geometry with a radius of R = 0.05m and a length of l = 1.0 m and use air at standard conditions. Run CFD simulations for Reynolds numbers of Re = 500, 2000, 4000, and 10,000. What effect does increasing the Reynolds number have on the total friction force on the pipe wall? By examining the calculated friction factors, *f*, explain the trend of how the friction factor varies as the Reynolds number is increased. Compare your calculated friction factors with the known values and comment on any differences.

Typical Results

This problem asks the students to use FlowLab for a fully-developed pipe flow problem at various Reynolds numbers. The software allows the students to visualize a wide variety of flow results, though the problem requires specific wall friction results. Depending on the Reynolds number, the students will either run FlowLab for laminar or turbulent pipe flow. A typical plot of the residual history for a turbulent simulation is shown in Figure 2.

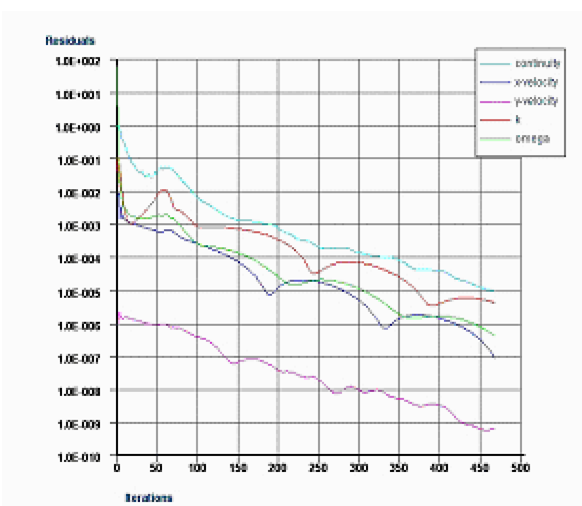

Figure 2. Residual history for turbulent pipe flow.

In calculating the total friction force, the students vary the Reynolds number and obtain the final friction force from the FlowLab results. The students can see that the total friction force increases with the increase in Reynolds number. The students are also asked to discuss the trend on the variation of the friction factor with Reynolds number. Figure 3 shows the computed friction factors as a function of Reynolds number, which gives the same trends as the standard Moody chart; a linear laminar region followed by an increase in the transition region and finally a decrease with further increases in the Reynolds number.

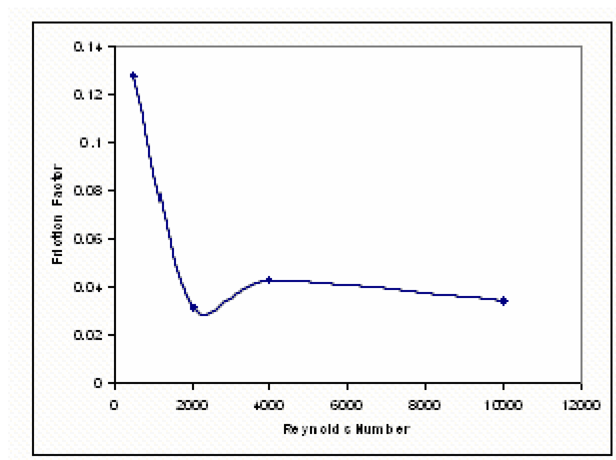

Figure 3. Variation of friction factor in a pipe with Reynolds number.

The final component of the problem is a comparison of calculated friction factors to published results. Table 1 summarizes the calculated friction factor values from the CFD analysis along with analytic comparison values. The equations used to calculate the friction factor for laminar and turbulent flow (Blasius formula) are given by the well known expressions:

$$f = {}^{64}\!/_{\mathrm{Re}} \text{ and } f = {}^{0.316}\!/_{\mathrm{Re}^{1/4}}\text{, respectively.}$$

For the first two Reynolds numbers, where the flow is laminar, the CFD simulations compare well to the laminar equation for friction factor. For the two turbulent flow cases, the computed results were compared to

Reynolds number	*f* - FlowLab	*f* - laminar (Eqn. 1)	*f* (Moody chart)	*f* - turbulent (Eqn. 2)
500	0.1278	0.128	n/a	n/a
2000	0.0319	0.032	n/a	n/a
4000	0.0430	n/a	~ 0.039	0.0397
10,000	0.0347	n/a	~ 0.03	0.0316

Table 1. Comparison of friction factor values.

the values from the Moody chart[9] and the Blasius equation. The computed *f* values are within 8-10% of the Blasius equation.

2. *Undergraduate - Fall 2005*

The students were given a basic pipe flow problem from Munson et al.[10], which is provided below. The introduction of the software was done during the class hours, and the FlowLab tutorial was also provided on-line. To enhance the understanding of how the software works and to resolve the problems that the students encountered, two class hours were done in the computer lab with teacher assistance.

Problem Statement

Use the FlowLab template pipe_el to investigate the flow field in the entrance length for pipe flow. Set the pipe geometry to a diameter of D = 0.1 m and length of l = 20 m. Use the default air properties for the fluid and set the grid to medium resolution. Conduct a parametric study to investigate how the Reynolds number affects the entrance length, l_e , for pipe flow. By varying the inlet velocity, U, obtain flow simulations for Re = 200, 400, 800, and 1000. Plot the wall friction factor distribution along the pipe and determine the friction factor, f, for the fully-developed region. Compare your friction factor values to the theoretical values, $f = 64/\mathrm{Re}$.

On top of the main problem, the students were given a bonus question: Consider the y-component of the velocity (v) at any cross-section in the entrance region; for simplicity, take the lower half of the pipe. The content of the flow field is going to be symmetric with respect to the center-line. Using the continuity equation and the viscous phenomena in the entrance region, explain the behavior of the y-component of the velocity (v).

Typical Results

The students used the FlowLab software to obtain solutions for a laminar flow in the specified pipe geometry at several Reynolds numbers. They determined the friction factor in the fully developed range both from the above equation and from the graphical interface provided by FlowLab that shows the variation of the friction factor along the pipe. They also determined the entrance length by using the equation $l_e/D = 0.06\,Re$, and the FlowLab graphical interface that shows the variation of the centerline velocity along the pipe. Typical values for the variation of the friction factor and the entrance length with the Reynolds number are shown in Table 2. For both parameters, the values obtained from the FlowLab are within 0 to 0.4 % error compared to the theoretical values.

Reynolds number	*f* - FlowLab	*f* - laminar (Eqn. 1)	l_e - FlowLab	l_e – laminar (Eqn. 3)
200	0.32	0.32	1.2	1.2
400	0.16	0.16	2.39	2.4
800	0.08	0.08	4.77	4.8
1,000	0.064	0.064	6.01	6

Table 2. Comparison of friction factor values, *f*, and entrance length values, l_e.

The bonus part included the explanation of the variation of the y-component of velocity within the entrance length. A sample plot of the v-velocity is shown in Figure 4 for the lower half of the pipe. As one proceeds from the wall surface towards the centerline, the v-velocity first increases from zero to a maximum value, and then decreases back to zero at the centerline. The students were expected to explain the increase and the decrease of the v-velocity. A brief explanation is as follows: If two points are considered that are at the same y location within the boundary layer, but at different axial locations within the entrance length, the axial velocity is going to decrease along the pipe due to the growth of the boundary layer; therefore, $\frac{\partial u}{\partial x} < 0$. Then, using the incompressible continuity equation, $\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0$, one concludes that $\frac{\partial v}{\partial y} > 0$, which explains the increase in the v-velocity in this region. As far as the decrease of v-velocity in the region that is closer to the centerline, consider again two points that are out of the boundary layer, at the same y location but different axial locations. Due to the growing boundary layer along the pipe, the centerline velocity is going to increase in order to conserve mass. Therefore, the u-velocity increases along the pipe, which means $\frac{\partial u}{\partial x} > 0$. Then, in order to satisfy the continuity equation, $\frac{\partial v}{\partial y} < 0$ must hold true, which explains the drop in the v-velocity as one approaches the centerline.

3. Graduate - Fall 2005

For the graduate viscous flow course, a new FlowLab problem was developed (from the available templates) that would hopefully be a bit more challenging than the standard undergraduate problems given in the two courses described above. The introduction of the FlowLab problem coincided with lecture material covering the standard Blasius boundary layer theory[12]. A brief FlowLab tutorial[10] was covered in class and the presentation was posted on-line for students to access. The students worked individually on the project and had ample access to the FlowLab software in three different computer labs.

Problem Statement

Using the plate template, run FlowLab to conduct an analysis of boundary layer flow over a flat plate. Use the following setup parameters for your study: plate length = 1 m; Reynolds number: $5x10^4$, $5x10^5$, $5x10^6$, $5x10^7$;

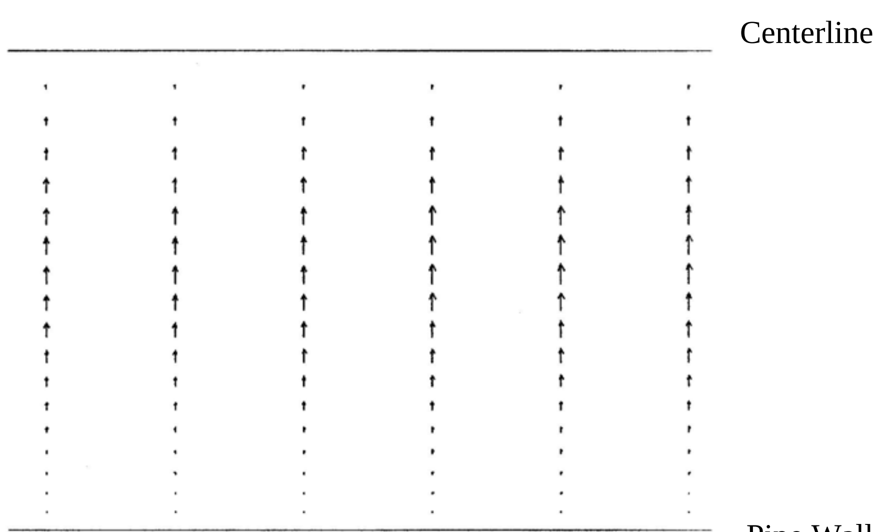

Figure 4. Variation of radial velocity in the lower half of a pipe.

fine grid and medium grid depending on Reynolds number; default convergence limits. Investigate the following aspects for flow past a flat plate:

1. Boundary layer height as a function of Reynolds number and compare results to analytic results.
2. Velocity profiles along the plate for laminar and turbulent flow.
3. Wall friction factor along the plate for laminar and turbulent flow.
4. Wall friction factor at end of plate for all Reynolds number values and a comparison to analytic results.
5. Contour plot of velocity magnitude for a laminar and turbulent case.
6. Plot of the final streamlines for laminar and turbulent case.

Typical Results

The students were asked to make use of the FlowLab software to simulate both laminar and turbulent flow past a flat plate, conduct a parametric study, and analyze the results. Though this is a relatively simple flow for a student in a graduate fluids course, the hope was that the students would gain better retention on the basics of boundary layer flow (e.g. if *Re* is increased, what happens to the boundary layer height, δ) and get a first exposure to the power of the CFD tool. To a lesser extent, it was thought to be a nice change from some of the higher-level theoretical problems they were required to solve in previous homework assignments.

Figure 5 shows the results of the wall friction factor comparison between FlowLab and the Blasius equation for laminar flow. The wall friction results compared well for all cases tested, while the boundary layer height had some error when comparing to the Blasius solution. The equations used for calculation of the wall friction factor for a flat plate are given as:

$$C_{f,x} = \frac{0.664}{\sqrt{\mathrm{Re}_x}} \text{ for laminar and}$$

$$C_{f,x} = \frac{0.455}{\ln^2\left(0.06\,\mathrm{Re}_x\right)} \text{ for turbulent flows.}$$

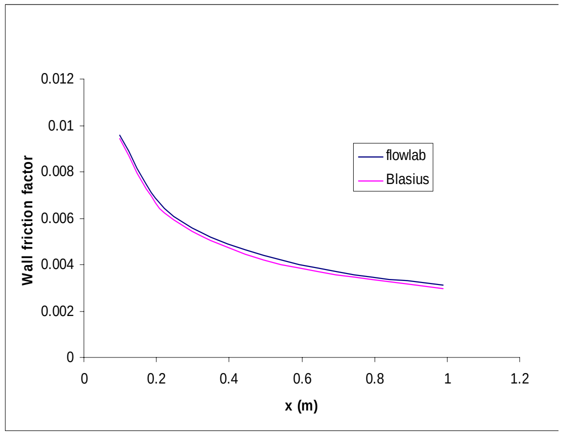

Figure 5. Comparison of the wall friction factor for Re = 5x10^4 between FlowLab results and Blasius values.

The students worked through the problem statement and wrote up a project report on their findings. Most of the operation of FlowLab and the analysis of the results were fairly basic for the students, other than the point described in the results section.

Course Results

1. Undergraduate

A basic tutorial was provided for the students during one lecture period, though to ease this fast process, the students were provided with the tutorial in advance and were asked to prepare for the lecture. The tutorial was presented on a working version of FlowLab, while explaining details of CFD as the tutorial progressed. Questions raised by the students were mainly concentrated on input and output data, especially how to post-process the results. FlowLab provides two options for output: automated graphing features or data output for use in another software. Although these output options are easy to learn, the main problem at the post-process step was that the students did not have enough experience with spreadsheet or graphics software.

In general, the tutorial was well received and regarded as “straight forward”. The students seem to have picked up the use of FlowLab easily, though the level of computer familiarity was a significant factor of stating “How easy?” The students were allowed to work in groups of two to encourage pair work and to ensure at least a minimum level of work for every student. According to the projects prepared by the students, a large majority of the students completed this task successfully, and some of them were also able to do the bonus part successfully with help from the instructor. Some of the projects were even considered excellent.

One observation from the implementation of the software as part of the course material was that the students had to do two things at once: learn the software and use it for the project. If this implementation was done in a large amount of time, such as throughout the semester, then it would be much easier for the students to handle. During both of the undergraduate implementations, the philosophy was to first give the students enough background on fluid mechanics, then have them do the project. However, with the pressure of other courses in the last weeks of the semester, it was not as beneficial as it could be. One suggestion at this point is to introduce FlowLab at the beginning of the semester and have the students use it at several points during the semester. This will give them ample amount of time to learn the software, and also will provide a virtual experimentation platform as new topics are covered in the class.

Another problem on the use of the FlowLab software was that the number of licenses was not enough as the entire class had to work on it during the same few last weeks of the semester. Several students also reflected this problem on their evaluations. Starting the use of the FlowLab earlier in the semester can also solve this problem.

2. <u>Graduate</u>

Overall, the students had little trouble working through the FlowLab project, even though it was their first introduction to the software, and for the most part, CFD. There was only one real problem involved in working through the project, which turned out to be somewhat of a blessing in disguise. One of the project requirements was to plot velocity profiles at various locations along the plate to show how the profile changes as a function of x. Some of the students plotted the u-velocity profiles at different locations, but noticed that at the top of the boundary layer, the velocity overshot the free stream value, then asymptoted back to this value moving farther from the plate surface. As it turned out, FlowLab sets up the vertical domain size as half of the plate length, L/2. With the problem statement specifying L = 1 m, the vertical domain was set to 0.5 m (instructor not being careful in setting up a new problem). This caused the flow to accelerate just outside of the boundary layer; setting L = 10 m solved this problem and the velocity profiles behaved as expected. The positive result was that this sparked some outstanding class discussion on boundary layers, conservation issues, and the idea of not taking CFD results as coming from a magic black box that can always be trusted; hence, one still needs a physical feel for the flow. So, though the project was relatively easy for the students, it did result in a deeper understanding of viscous boundary layer flow.

Student Feedback

1. <u>Undergraduate</u>

The questions that constituted the survey are as follows:

1. I have a basic understanding of what computational fluid dynamics (CFD) involves.
2. The FlowLab software was easy to use in running simulations.
3. The FlowLab software was easy to use for outputting results.

4. The use of FlowLab in the class contributed to my understanding of fluid mechanics.
5. The results from FlowLab helped to reinforce topics from the lecture.
6. The visualization capabilities of FlowLab helped me to better understand fluid flow phenomena.
7. I now feel comfortable using FlowLab.
8. I have a better understanding of making comparisons between computational and experimental results.
9. I would recommend continuing the use of FlowLab in the fluids course.
10. I would recommend expanding the use of FlowLab in the fluids course.

The average of the responses for each question is provided in Figure 6. The average standard deviation for these responses was 0.11 showing that the answers of the students were not much different from the averages given in Figure 6. The student survey shows that the term project with the use of the FlowLab software was overall evaluated as average or above-average. The reason for not reaching the excellent level is thought to be due to having the students both learn the software and fluid mechanics at the same time when they are also supposed to go through the examinations of other classes. Nevertheless, the project made a nice introduction to CFD for most of the students and enhanced their understanding of the fluid flow phenomena. The parts of the course material that are relatively abstract, such as boundary layer growth, were reinforced with the use of FlowLab as a tool for virtual exploration.

The Navier-Stokes equations, which are considered as untouchable due to their partial differential character, were solved with the use of CFD, in this case with FlowLab. This alternative seemed more student-friendly as compared to the overwhelming image of the partial differential equations. The students seemed to like this way of learning, as even generally less interested students got involved at a satisfactory level. Most of the students were enthusiastic of having a visualization tool like FlowLab available for them to support a

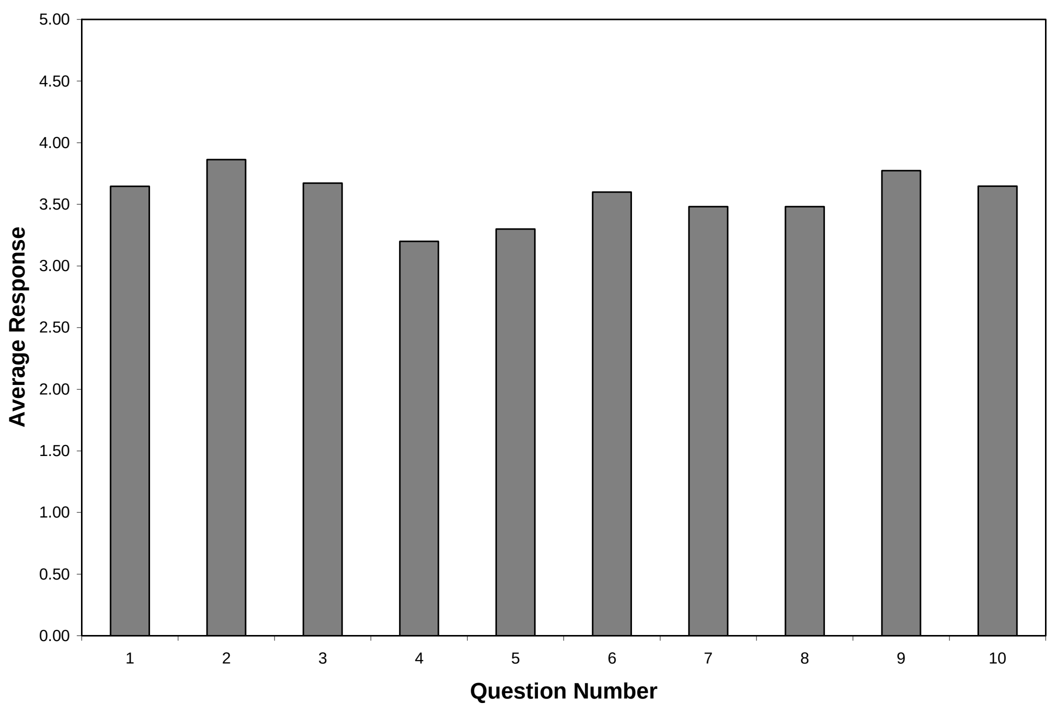

Figure 6. Results from FlowLab survey in the undergraduate fluid mechanics course; Spring and Fall 2005.

fluid mechanics course. They also learned to distinguish between laminar and turbulent flow as the velocity profile was changing with increasing Reynolds number. In addition, they learned how to compare the simulations with available experimental data; actually FlowLab provided them with the opportunity to perform “experiments” without going to an actual laboratory. This opportunity seemed to strengthen the learning of how the friction force and friction factor is changing with fluid velocity, i.e. how the Moody Chart is used.

2. Graduate

The same questionnaire was given to the graduate students, with two additional questions given below:

11. Conducting a virtual fluids experiment such as this has helped me to have a better intuitive feel for viscous flows.
12. I feel that my retention on the boundary layer concepts covered in this project has been improved due to the use of FlowLab.

The results of the survey are shown in Figure 7. The average standard deviation on these responses was 0.21. There are some qualitative thoughts that can be drawn from these results. In terms of FlowLab contributing to the understanding of fluid mechanics and helping to reinforce lecture topics, the students somewhat agreed. For the most part, the students agreed on the use of FlowLab in the course for a project type assignment, but were not as enthusiastic about the expansion of the use of FlowLab. With the basic viscous flow material that needs to be covered in such a course, there is not much room for expansion even if the students favored such a move. It would seem that the use of FlowLab in a graduate fluids course would benefit from more complex flow templates (geometry and/or flow field) that the students could use. A final point to make is that a majority of the students felt that the use of FlowLab improved their intuitive feel for viscous flow and that their retention on boundary layers concepts was improved. It is the authors’ opinion that the

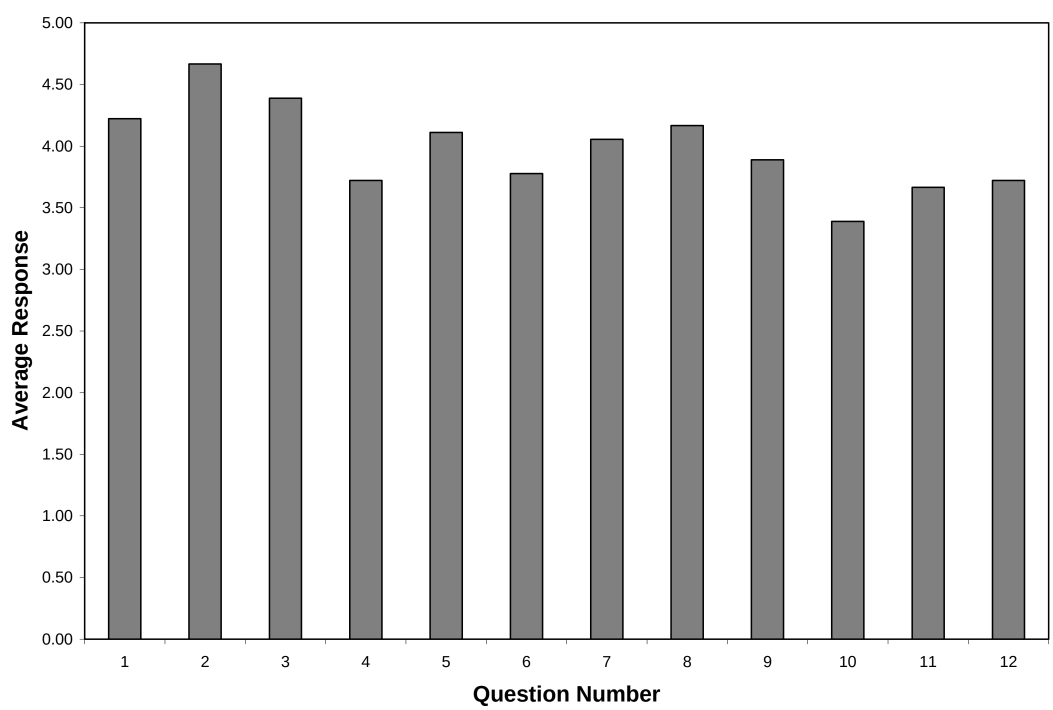

Figure 7. Results from FlowLab survey in the graduate viscous flow course, Fall 2005.

FlowLab component should continue to be used, but remain a small portion of the overall workload of the course. It is likely that future FlowLab problems for the graduate fluids course will be more complex on some level to challenge the students more than the previous problem. Several written comments on the surveys also indicated that the software should be introduced prior to assigning the project, which reinforces experiences from the undergraduate course.

Conclusions

Overall the implementation of FlowLab into the three courses described in this work was fairly smooth and generally well received. One of the true strengths of FlowLab is the short learning curve required to get students simulating flow fields and analyzing results. If you are teaching a fluids course, other than CFD, you cannot afford to spend a large portion of time on either the theory of CFD or learning a complicated software tool, when you just need a homework problem, or project, or a virtual experiment to augment the lecture material. These initial attempts at implementing FlowLab into several fluids courses seem to indicate that it is a good tool for this purpose.

Several specific points were concluded from the implementation process and are summarized below.

- FlowLab exercises provide a reasonable framework to expose non-expert students to CFD in lecture based or laboratory courses, requiring only a small investment of time for learning the software.
- FlowLab also provides a nice platform to perform virtual fluids experiments where the students can easily conduct various parametric studies.
- Preliminary data suggests that there is some level of curriculum enhancement with the addition of FlowLab into fluids courses.
- FlowLab should be introduced prior to homework or project assignment. A simple set of exercises could be developed to introduce FlowLab early in the course and have students start to use it. These could include such features as visualization of velocity vectors, streamlines, velocity profiles, pressure contours, etc.
- Basic FlowLab problems may be a bit too rudimentary for a graduate viscous flow course, though development of more complex FlowLab templates may remedy this situation.
- FlowLab will continue to be a component, albeit a small one, in the two fluids courses.

Information on FlowLab Acquisition

FlowLab is distributed by Fluent Inc. Pricing and licensing information may be requested at the FlowLab website, www.flowlab.fluent.com. FlowLab is serving as a companion CFD tool for three fluid mechanics textbooks: Fundamentals of Fluid Mechanics, 5th Ed., published by Wiley; Fluid Mechanics, Fundamentals and Applications, 1st Ed., published by McGraw-Hill; and Fluid Mechanics for Chemical Engineers, 2nd Ed., published by Prentice Hall. More information about how these textbooks use FlowLab to convey CFD and fluid mechanics methodology is available at the FlowLab website:
http://flowlab.fluent.com/collaborations/index.htm

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