Hands-On CFD Educational Interface for Engineering Courses and Laboratories

FREDERICK STERN
IIHR-Hydroscience & Engineering
The University of Iowa

TAO XING
IIHR-Hydroscience & Engineering
The University of Iowa

DONALD B. YARBROUGH
Center for Evaluation and Assessment
The University of Iowa

ALRIC ROTHMAYER
Aerospace Engineering
Iowa State University

GANESH RAJAGOPALAN
Aerospace Engineering
Iowa State University

SHOURYA PRAKASH OTTA
Aerospace Engineering
Iowa State University

DAVID CAUGHEY
Mechanical and Aerospace Engineering
Cornell University

RAJESH BHASKARAN
Mechanical and Aerospace Engineering
Cornell University

SONYA SMITH
Mechanical Engineering
Howard University

BARBARA HUTCHINGS
Fluent Inc.

SHANE MOEYKENS
Fluent Inc.

ABSTRACT

This study describes the development, implementation, and evaluation of an effective curriculum for students to learn computational fluid dynamics (CFD) in introductory and intermediate undergraduate and introductory graduate level courses/laboratories. The curriculum is designed for use at different universities with different courses/laboratories, learning objectives, applications, conditions, and exercise notes. The common objective is to teach students from novice to expert users who are well prepared for engineering practice. The study describes a CFD Educational Interface for hands-on student experience, which mirrors actual engineering practice. The Educational Interface teaches CFD methodology and procedures through a step-by-step interactive implementation automating the CFD process. A hierarchical system of predefined active options facilitates use at introductory and intermediate levels, encouraging self-learning, and eases transition to using industrial CFD codes. An independent evaluation documents successful learning outcomes and confirms the effectiveness of the interface for students in introductory and intermediate fluid mechanics courses.

Keywords: computer-assisted learning, hands-on CFD Educational Interface, simulation technology

I. INTRODUCTION

There is no question of the need and importance of integrating computer-assisted learning and simulation technology into undergraduate engineering courses and laboratories, as simulation-based design, and ultimately virtual reality, become increasingly important in engineering practice. The scope of simulation technology is broad covering computerized systems and computerized solutions of engineering problem formulations using mathematical physics modeling, numerical methods, and high performance computing; all of which broadly influence all engineering disciplines. Recent research has shown the effectiveness of computer-assisted learning for accounting tutorials [1], food process design projects [2], electrical machines laboratories [3], the use of multi-media courseware for bicycle dissection [4] and scrapers [5], and an on-line internal combustion engine research facility using both computations and experiments [6]. Systems-based simulation technology has also shown to be effective for chemical plant design [7], electronics laboratories [8], and chemical processes [9], including the use of commercial software for chemical processes [10] and educational computer programs for mechanical systems [11] and neural networks [12]. Methods for assessing the effectiveness of using simulation technology in engineering education include student presentations, surveys, and interviews; student performance, including pre- and post-tests both with and without intervention; statistical analysis; and faculty perception.

With respect to employing simulation technology in the curriculum, consideration must be given to issues of: learning vs. research objectives; usability vs. predetermined objectives; and student demographics. Previous studies focusing on use of simulation technology in education have shown enhancement of the curriculum [1–12]; increased learning efficiency and understanding [7, 8, 10]; effectiveness of novel and hands-on learning methods [4]; efficacy of combined physical and simulation laboratories [8]; importance of user-friendly interfaces [5, 11]; and positive student responses [7, 10]. Curricula must be developed for physics-based simulation technology, such as computational fluid dynamics (CFD), which is of present interest, but diverse learning objectives and limited research both are complicating factors for successfully incorporating CFD into the curriculum. CFD is a widely used tool in fluids engineering, with many specialty and commercial CFD codes in use through out the world, covering many application areas. The lack of trained users is a major obstacle to the greater use of CFD.

In parallel with the use of CFD for research and development activities over the past 35 years, graduate student level CFD courses have become well developed and common in most engineering discipline graduate programs. Intermediate and advanced level CFD courses teach modeling and numerical methods using textbooks, computer-programming assignments, and specialty [13–15] or commercial software [16–18]. These courses have a common objective of learning CFD for code development and applications in support of M.S. and Ph.D. thesis research. More recently, as CFD becomes pervasive in engineering practice and engineers are expected to use it without post-graduate education, educators have additionally focused on teaching CFD at the undergraduate level. Various curricula have been developed, including CFD courses, laboratories, and/or projects and multi-media [19, 20], studio models [21, 16–18], and computerized textbooks [22]. These curricula use both specialty [23, 24] and commercial [16–18, 25–27] software, which is sometimes combined with experiments [16, 27]. Additionally, the curricula frequently cover a diverse range of learning objectives. A graduate student intermediate level CFD course is generally also open as a technical elective to undergraduate students, while the curriculum is optimized separately for the graduate or undergraduate groups. Integrating specialty or commercial CFD software for the non-expert user into lecture and/or laboratory courses can facilitate comparisons with experiments and analytical methods. The objective is to enhance the curriculum through use of interactive CFD exercises, multi-media, and studio models for teaching fluid mechanics, including heat transfer and aerodynamics. A limited evaluation following the aforementioned methods shows promise, with achievements as noted in the previously mentioned studies at both graduate and undergraduate levels.

However, there remain many unresolved issues. For example:

1. When is the hands-on and discovery-oriented approach to be preferred over demonstration?
2. When does CFD detract from, rather than aid, the development of deeper knowledge of fundamental fluid mechanics concepts?
3. How can student perception of CFD as a black box be avoided, and understanding of detailed CFD methodology and procedures be promoted?
4. Should specialized educational software replace the use of commercial software?
5. How can the steep learning curve required for practical engineering applications be mitigated?
6. What are the best approaches for introductory vs. intermediate undergraduate and intermediate vs. advanced graduate level courses?
7. When is lecture and laboratory course teaching more appropriate than the studio and multi-media models?
8. What is the best curriculum content for teaching code developers vs. expert users?

The most effective curricula to achieve optimal CFD education remain unspecified, partly due to the limited evaluation and assessment performed to date.

This research focused on the development, implementation, and evaluation of an effective curriculum for students to learn CFD in introductory and intermediate undergraduate and introductory graduate level courses/laboratories. The curriculum is designed for use at different universities with different courses/laboratories, learning objectives, applications, conditions, and exercise notes. The common objective is to teach students from novice to expert users who are well prepared for engineering practice. This also accommodates all previously mentioned learning objectives, except for computer programming. Here, an expert user is a person well qualified to enter engineering practice as a CFD engineer. Incorporation of commercial industrial software such as CFX, FLUENT, and StarCD can expose students to the same or similar software they may use as professionals in industry. To allow students early hands-on experience, while avoiding the steep learning curve typically associated with any sophisticated software system, and to avoid having students treat the software as a black box required development of an Educational Interface. Here, hands-on is the use of a CFD engineering tool to achieve a meaningful learning experience that mirrors real-life engineering practice. The CFD Educational Interface developed in this study teaches CFD methodology and procedures through the step-by-step interactive implementation that automates the CFD process. A hierarchical system of predefined active options, which facilitates the use of the Educational Interface at introductory and intermediate levels, encourages students' self-learning, and eases the transition to using industrial CFD codes. A later section (IV) reports the independent evaluation of these educational tools conducted through collaboration with the University of Iowa, Center for Evaluation and Assessment (CEA). Our industrial partner, Fluent Inc [28], is disseminating the CFD Educational Interface and associated exercise notes.

Section II explains the concept of the CFD Educational Interface, including the development process that lead from using FLUENT and unmodified FlowLab directly to the development of the CFD Educational Interface; design specifications; detailed features and differences compared to FLUENT and unmodified FlowLab; and prototype capabilities. Section III describes the implementation and refinement of the CFD Educational Interface at partner sites. The different universities, course/laboratories, learning objectives, applications, conditions and exercise notes are described, which provides evidence of the versatility of the CFD Educational Interface. More details are given for one of the sites since it was at this site where both formative and summative evaluation occurred. Section IV presents the evaluation design and results, including formative evaluation at all sites, summative evaluation and outcomes assessment at one site, and overall conclusions and discussion. Limitation of resources precluded collecting pre- and post-test achievement data at all sites; however, based on summative survey results (skill and efficacy ratings) and their convergence with the knowledge test data from Site 1 (The University of Iowa), it is reasonable to assume similar outcomes at the partner sites. Lastly, Section V provides conclusions and future work, including discussion of previously listed unresolved issues regarding those addressed by the CFD Educational Interface and those remaining to be addressed.

While the research is focused on a subject of special interest to some but not all engineering disciplines (CFD), it is offered as a case study of the application of similar industrial software in other engineering fields.

II. CFD Educational Interface

The concept of a CFD Educational Interface resulted from the authors' collaboration on the development, site testing, and evaluation of teaching modules (TMs) for complementary CFD, experimental fluid dynamics (EFD), and uncertainty analysis (UA). The project, entitled Integration of Simulation Technology in Undergraduate Engineering (ISTUE), was sponsored by the National Science Foundation from March 2002 through February 2005. An earlier proof of concept study (1999–2002) used FLUENT directly. Introducing FLUENT to novice users required lengthy detailed instructions. Some users were confused by the many parameters that were required to be set, many of which were often unrelated to the particular student application of interest and difficult to explain. Because experienced users can perform such tasks manually, the FLUENT interface did not provide automated options for modeling, numerical methods, and verification and validation studies, as desired for learners in the current study. Such automation could have been developed for FLUENT directly. However, because pre-processing is handled by a separate application, GAMBIT, other avenues for developing an Educational Interface were considered.

The initiation of the collaboration coincided with Fluent's release of FlowLab version 1.0 (2002). FlowLab is designed as a general-purpose CFD template, which allows students to define a geometry, specify physics, mesh the domain, and solve CFD models using predefined exercises. During the first year of the project, faculty partners collaborated with Fluent on setting up CFD templates for their respective learning objectives, courses, and/or laboratories with an agreed focus on introductory undergraduate level pipe flow and airfoil exercises. This initial work was performed using unmodified FlowLab version 1.0 (the 2002 release version). After completing a capabilities review of these exercises, and upon coming to an agreement regarding a systematic CFD process in the context of the requirements of the present initiative, faculty partners and Fluent implemented modifications to the FlowLab operations menu to conform with the agreed upon requirements of the CFD process. This work also included verifying the accuracy of results from the templates for specific applications, including making comparisons with analytical and experimental validation data. Interim evaluations in 2002–2003 confirmed that the implementation was worthwhile and promising, but also identified opportunities for improvement. The use of different specialized CFD templates for each exercise did not directly facilitate adherence to the previously agreed upon CFD process, and these differences further complicated site testing. Additionally, these initial exercises lacked options and depth, and were overly automated in some instances, giving students a black box impression of CFD. Some aspects of the interface were not very user-friendly, and solution accuracy and the quality of flow visualization were substandard relative to the requirements of the present initiative. Anonymous student responses suggested that the EFD, CFD, and UA labs were helpful to their learning of fluid mechanics and provided practice with important tools that they may need to use as professional engineers. However, they also reported that they wanted the learning experience to be more hands-on and tailored to their personal learning needs. This formative feedback led to development of the CFD Educational Interface, which among other objectives, provided a vehicle for more close adherence to the agreed upon CFD process. This activity was of direct benefit to Fluent in that the operations menu for unmodified FlowLab exercises was updated to conform with the CFD Process, requiring physics options to be specified prior to developing the computational mesh. Selected formative evaluation comments from students based on their use of FLUENT, unmodified FlowLab, and the CFD Educational Interface are listed in Table 1.

A. Design Specifications

The CFD Educational Interface is designed to teach students systematic CFD methodology (modeling and numerical methods) and procedures through hands-on, user-friendly, interactive implementation of practical engineering applications, while not requiring computer programming. The CFD process is automated, following a step-by-step approach which leads students seamlessly through setup and solution of the initial boundary value problem (IBVP) appropriate for the application at hand. The CFD process mirrors actual engineering practice: geometry (solid and other fluid boundaries), physics (compressible/incompressible, with/without heat transfer, fluid properties, modeling, initial and boundary conditions), mesh specification (structured/unstructured, manual/automatic meshing), solution procedure (numerical parameters, solution convergence monitoring, different numerical schemes), and reports/post-processing (flow visualization, analysis, verification, validation using imported EFD data and uncertainties). A hierarchical system of predefined active options facilitates the use of exercises at both introductory and intermediate levels, and encourages students' self-learning. Enough information is provided to ease the student transition from this intermediate level to using the full FLUENT (or any other industrial CFD) code directly. A static sketch window is used to illustrate the flow problem currently being investigated. Generalization of internal and external flow templates to inter and multi disciplinary applications facilitates their use at different universities having different objectives, applications, conditions, and exercise notes.

B. Features

The hands-on CFD Educational Interface has the following features:

1) User-friendly and interactive interface: The interface design is in the objective-oriented mode with interactive interfaces and smooth data transformations.

2) Follows exactly the "CFD Process": The software orients students to setup, solve and analyze CFD problems step-by-step, while conforming to the CFD Process as defined by collaborating faculty partners.

FLUENT (1999~2002)	Unmodified FlowLab (2002~2003)	CFD Educational Interface (2003~2005)
1. CFD: worthless. 2. FLUENT was hard to understand. 3. I do not understand why I was doing what I was doing. 4. CFD needs to be simplified. 5. CFD labs were difficult without TAs' help. 6. I would recommend a little more overview of what the software is doing (i.e., how an input variable effects output). 7. There are so many settings and variables in this software it was hard to determine the sources of error in the calculated data.	1. Need a better way to import EFD data and suggest input data on screen. 2. FlowLab is confusing. 3. The main problem we had is with gathering the figures. 4. For some unknown reason, the CFD software would not properly compute the flow properties of an angle of attack of 0 degrees. 5. Students stand. I want the lab to be as much "hands-on" as possible. 6. I prefer to work on this lab independently. 7. CFD labs are hard to understand what was going on.	1. Data comparison between CFD and EFD is effective for more understanding of fluid mechanics. 2. Hands-on was very helpful and beneficial to learn CFD process and provide the students with a better understanding into the complex field of fluid mechanics. 3. Valuable experience to learn CFD. 4. Visualizations of flow physics are effective. 5. Can learn setting up the CFD software. 6. The software is a very user-friendly interface that made rapid setup and program execution move smoothly. 7. I enjoy the self-study. 8. I have learned a lot from the CFD simulation, today, it is easier for me the handling of the CFD process than at the beginning of the semester. 9. The design of this interface eases the CFD learning especially for beginners. 10.The knowledge I acquired by doing these CFD simulations will carry through future work of my engineering career, I will be faced with and prepared for.

Table 1. Selected student comments on using FLUENT, unmodified FlowLab, and the CFD Educational Interface.

3) No requirement for advanced computer language skills: The interface is designed to help students focus on CFD methodology and procedures following the CFD process.

4) Stand-alone application: Unlike most CFD commercial software that requires different software applications to perform grid generation, solving, and post-processing, this Educational Interface combines all of the necessary steps to define and solve an Initial Boundary Value Problem (IBVP).

5) Compatible with Microsoft Operating Systems: Student familiarity with Microsoft Operating Systems facilitates the learning and the use of this interface. The interface allows a user to copy, paste, and import or export data. Figures/Data can be edited in popular Microsoft software, such as WORD, EXCEL, and NOTEPAD.

6) Different depths of CFD templates: Options for CFD templates are designed in such a way that they can be used at both introductory and intermediate levels.

7) Hands-on: Students interact with the software using mouse and keyboard input. Students use CFD, EFD and UA engineering tools in a meaningful learning experience, which mirrors as closely as possible a real-life engineering practice.

8) Self-guided studies: The teaching modules are designed to meet students' requirements on self-learning.

9) Powerful and accurate solvers: The interface was built on top of GAMBIT and the solvers applied are the same as the solvers used in the commercial software FLUENT.

10) Powerful virtualization tools: Virtual reality tools enhance students' understanding of fluid physics. The CFD Educational Interface uses GUI tools to plot contours, vectors, streamlines and make animations.

11) CFD uncertainty analysis: For the first time, CFD verification and validation tools are incorporated into an Educational Interface to enable students to learn the basic theory of CFD Uncertainty Analysis.

12) Sketch window: This feature illustrates the geometry and boundaries with all of the nomenclature that will be used in the simulation.

The primary differentiators between FLUENT, unmodified FlowLab and the CFD Educational Interface are illustrated in Table 2 for the twelve features listed above.

C. Prototype

The prototype for the CFD Educational Interface was constructed using FlowLab versions 1.1 (2003) and 1.2 (2004) to create common CFD templates for flow in pipes, with and without

Features	FLUENT	Unmodified FlowLab	CFD Educational Interface
1	Yes, but with many options that introductory level students will not use. This can be problematic for novice users.	Yes	Yes, while providing greater depth and functionality than the standard FlowLab interface.
2	No, does not strictly comply with the CFD process as implemented in the Educational Interface.	No, does not strictly comply with the CFD process as implemented in the Educational Interface; for example, lacks verification capability.	Yes
3, 5, 9, 10	Yes	Yes	Yes
4	No, needs GAMBIT to generate geometry and grid.	Yes	Yes
6	Not available, educational templates do not exist for use with FLUENT. Tutorials are available from Fluent, but these materials do not possess the same depth as the TMs developed in the present study.	No, standard FlowLab exercises have been developed without specific provision for intermediate or advanced users.	Yes
7	Not available, educational templates do not exist for use with FLUENT.	No, standard FlowLab templates don't directly facilitate verification and UA activities.	Yes
8	Not available, educational templates do not exist for use with FLUENT.	Yes, complementary exercise notes exist for standard FlowLab exercises.	Yes, exercises and accompanying TMs provide greater depth and flexibility vs. standard FlowLab exercises.
11	Yes, but uncertainty analysis must be performed manually.	No	Yes, with automation to facilitate the process.
12	No	No	Yes

Table 2. Different features for FLUENT, unmodified FlowLab, and the CFD Educational Interface.

heat transfer; for compressible flow in a nozzle with shock waves; flow in a diffuser; flow past a circular cylinder; flow past an airfoil; and the Ahmed car with unsteady separation. Students interact with the software using mouse and keyboard input following the systematic CFD process. The CFD Educational Interface combines software tools for grid generation, flow solving, and post-processing to establish and solve an IBVP. The student's familiarity with menu-driven software systems facilitates the easy use and learning of the interface. All functions of the interface, such as copy and paste of the figures and import and export data, are conducted using commonly available office software (WORD, EXCEL, and NOTEPAD). The FlowLab interface was built on top of the Fluent grid generation software, GAMBIT, and the solvers are the same as those used in the commercial version of FLUENT. The interface uses GUI tools to plot contours, vectors, streamlines and to make animations. Verification and validation tools are included for teaching CFD uncertainty analysis. Figure 1 shows a screen image of the pipe flow template at a specific step of the CFD process. Figure 2 is a flow chart showing the combined capabilities of the current CFD templates, as are described next.

1) Geometry: Students can create different geometries and domains, including: (a) pipe, (b) nozzle, (c) airfoil (Clark Y, NACA 0012, LS(1)0417, or import geometry data), (d) diffuser (asymmetric or axisymmetric), and (e) 2D Ahmed car body. Students need to input different parameters for the particular class of geometry they have selected, such as pipe (radius and length), nozzle (inlet/outlet/throat radius, converging/diverging/outlet length, plenum length/radius), airfoil ("O"/"C" mesh topology, chord length, angle of attack), diffuser (inlet/outlet dimension/length, diffuser angle), and Ahmed car (slant angle, upstream/downstream length, domain height, gap). All geometry and domain parameters are illustrated in the sketch window (the pipe example is shown in Figure 1).

2) Physics: Students need to choose whether to model the flow as compressible/incompressible, with/without heat transfer, as inviscid/viscous, and as laminar/turbulent; set up the fluid properties

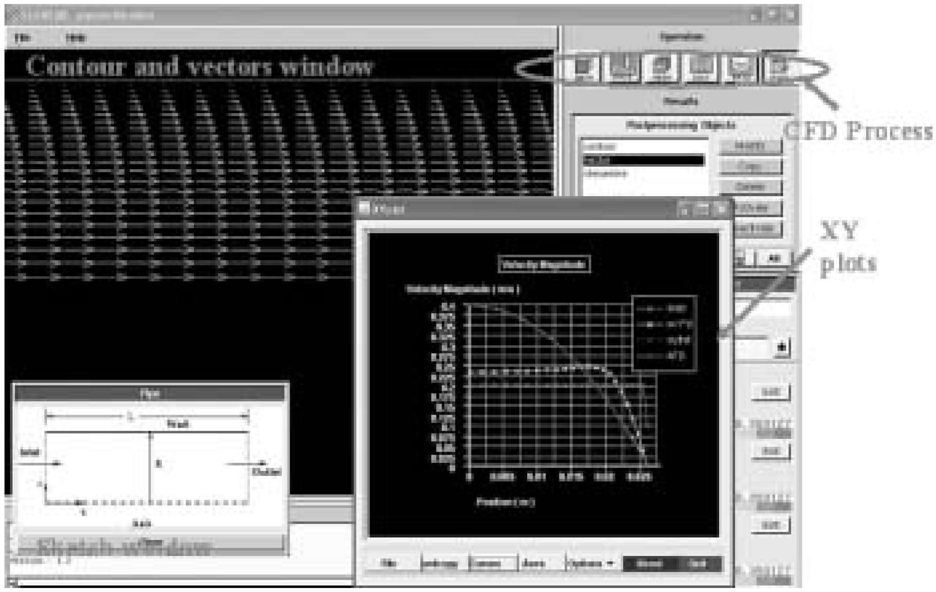

Figure 1. Screen image for the pipe flow CFD template.

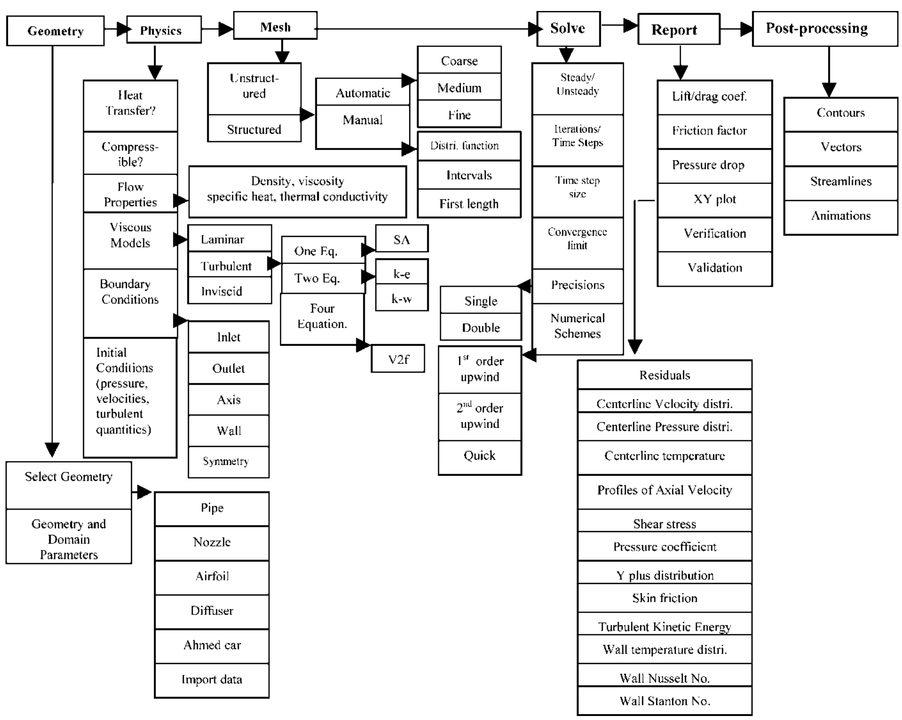

Figure 2. Flow chart for the combined CFD template.

(density, viscosity, specific heat, thermal conductivity); select appropriate turbulence models, if appropriate (S-A, k-epsilon, k-omega, V2F); and define boundary conditions (inlet, outlet, symmetry, wall, axis) and initial conditions. Students are required to specify all the variables (velocities, pressure, temperature, heat flux, turbulent quantities) on all boundaries using constant values, zero gradient, or specified distributions in order to emphasize and investigate the role of boundary conditions in well-posed IBVPs.

3) Mesh: Both structured and unstructured meshes are available. When using structured meshes the student either automatically or manually generates the desired meshes. Automatic meshing is designed for novice/introductory level students, who lack the basic knowledge of the methodology and procedures of mesh generation. By specifying "coarse," "medium," or "fine" meshes, the Educational Interface will automatically generate a mesh of the corresponding density using parameters hard coded in the software. Manual meshing is designed for professional/intermediate level students. To use this feature, students need to define the boundary grid by specifying the number of grid points, the grid spacing, and grid distribution functions for each boundary. This procedure is consistent with the steps and methodology applied in most commercial CFD software.

4) Solve: Students need to specify appropriate solution parameters. These include whether the flow is to be treated as steady or unsteady, maximum iteration count, convergence limit, numerical precision (single/double), spatial difference scheme (1st order, 2nd order, QUICK scheme), and axial output locations (for output variables to compare with EFD).

5) Reports: After the iterative solution process converges, all the integral parameters of the solution, such as total forces and lift/drag coefficients, are reported. Various XY plots and verification and validation functions are also available for students to validate their simulations using benchmark, or their own, EFD data, and to conduct CFD uncertainty analysis. Available XY plots include axial velocity profiles, pressure coefficient distributions, centerline pressure/velocity distribution, shear stress, Y plus, wall friction factor, and wall temperature/Nusselt number. The total reduction in magnitude of solution residual and final level of solution residual are used to determine stopping criteria for the iterative solution process. For unsteady flows, the time history of integral variables (e.g., drag force) is used to determine the degree of convergence of the iterative solution. At the introductory level, grid uncertainty is analyzed using only two meshes generated by the automatic function of the interface (coarse and medium, or coarse and fine). At the intermediate level, at least three meshes (generated either "automatically" or "manually") are used to quantitatively calculate grid uncertainties using Richardson Extrapolation. Grid refinement ratio can also be used to create different sets of meshes. In the future, reports will be combined with post-processing.

6) Post-processing: Powerful tools can be used to visualize and examine the flow field, such as contours (total/static pressure, velocities, Turbulent Kinetic Energy, temperature, Mach number), vectors, streamlines, and animations. Animations can be used only for unsteady separated flows at the intermediate level course.

III. Implementation and Refinement at Partner Sites

The CFD Educational Interface has been implemented at different universities with different courses/laboratories, learning objectives, applications, conditions, and exercise notes for introductory and intermediate undergraduate, and introductory graduate level courses and laboratories over the past three years in conjunction the development of TMs for the ISTUE project. Teaching Modules have three parts: (1) lectures on CFD, EFD, and UA methodology and procedures; (2) hands-on CFD Educational Interface for academic use of commercial industrial CFD software; and (3) exercise notes for use of CFD Educational Interface and complementary EFD and UA.

Faculty partners are from colleges of engineering at large public, small private, and small historically minority private universities in departments of mechanical and industrial, aerospace, mechanical and aerospace, and mechanical engineering. Faculty partners developed TMs for their respective courses/laboratories using the same CFD Educational Interface. Courses/laboratories include introductory (all three years) and intermediate (the Fall of 2004) level fluid mechanics at The University of Iowa, introductory gas-dynamics laboratory and introductory aerodynamics laboratory at Iowa State University, intermediate fluids mechanics and heat transfer laboratory at Cornell University, and intermediate fluid mechanics at Howard University.

Upon initiation of the ISTUE project, the faculty partners' primary learning objectives were to integrate commercial CFD for non-expert users into lecture and/or laboratory courses, including comparisons with experiments and analytical methods, and to enhance the curriculum with CFD as an instructional tool for increased knowledge. Over the course of the project, the objective shifted to teaching CFD from novice to expert users well prepared for engineering practice using CFD Educational Interface, which accommodates the former objectives. Although all the faculty partners used the same CFD Educational Interfaces, the actual implementation varied considerably depending upon the course at hand and the faculty member's preferred teaching approach. The following will present an overview of the courses at all partner universities, but with The University of Iowa as a more detailed example.

The introductory level fluid dynamics course at The University of Iowa is a four-semester hour junior level course, required of all students in mechanical and civil and environmental engineering and frequently elected by biomedical engineering students. Traditionally, the course used four lectures per week for analytical fluid dynamics (AFD) with a few additional EFD labs for highlighting fundamental principles. The course was restructured to consist of three-semester hours of AFD (3 lectures per week) and one-semester hour (one laboratory meeting per week) of complementary EFD, CFD, and UA laboratories, with detailed course, EFD and CFD lab learning objectives (Appendix A). The course is offered in both fall and spring semesters with about 65 and 15 students, respectively, with different professors in spring and fall, and four and two teaching assistants, respectively. The pipe and airfoil flow CFD Educational Interfaces were used. Three lectures were used to prepare the students for the complementary laboratories. At the start of course, AFD, EFD, and CFD are introduced as complementary tools of fluids engineering practice. At the start of EFD laboratories, EFD methodology and procedures are presented. At start of CFD laboratories, CFD methodology and procedures are presented. The CFD lectures cover what, why, and where is CFD used; modeling; numerical methods; types of CFD codes; the CFD process; an example; and an introduction to the CFD Educational Interface and student applications. The laboratories for fluid properties and EFD UA (EFD only), pipe flow (EFD and CFD), and airfoil (EFD and CFD) flow were sequential from the beginning to the end of the semester, with increasing depth. Detailed exercise notes guide students step-by-step on how to use the Educational Interface to achieve specific objectives for each lab, including how to input/output data, what figures/data need to be saved for the lab report, and questions that need to be answered in the lab report. CFD lab report instructions (Appendix B) guide students step-by-step through how to present their results and findings in written and graphical form. Lectures and exercise notes are distributed through the class Web site [29]. CFD concepts covered in pipe and airfoil exercise notes were developed to meet the learning objectives of course, EFD and CFD Labs (Appendix A). CFD concepts for pipe flow are definition of CFD process, boundary conditions (inlet, outlet, wall, axis), iterative and grid convergence, developing length and fully developed velocity profiles of laminar and turbulent flow, effect of single/double precision, verification using AFD for laminar flow, and validation using students' own EFD data for turbulent flow.

The CFD concepts for airfoil flow are boundary conditions (inlet, outlet, symmetry, airfoil), pressure coefficient and lift/drag coefficients, inviscid vs. viscous flow, effects of angle of attack, effects of turbulence models, and validation using students' own EFD data. Student performance was evaluated based on their CFD Lab reports and pre-lab and post-lab testing. The CFD Lab report covers the purpose of the experiment and design of the simulation, the CFD process, data analysis and discussion, and conclusion. Pre- and post-tests cover the concepts students are expected to learn in the complementary laboratories (22 AFD, 19 CFD, and 22 EFD questions). All questions provided multiple alternatives of which only one choice was correct. Some questions may ask students to write down their own answer if none of the choices is correct. After choosing the answer for each question, students indicated how confident they were of their answer by circling a number on the confidence scale below that item, i.e., "completely confident," "somewhat confident," "not at all confident," and "just guessing."

The intermediate level fluid dynamics course at The University of Iowa is a three-semester hour senior undergraduate and first-year graduate level course elected by mechanical, civil and environmental, and biomedical engineering students. Traditionally, the course used three-lectures per week for AFD. The course was restructured for addition of the CFD lectures and laboratories, which count for one-third of the course grade. Detailed course and CFD lab learning objectives are presented in Appendix C. The course is offered in the fall semester with about 39 students, one professor, and one teaching assistant. The pipe, airfoil, diffuser, and Ahmed car flow CFD Educational Interfaces were used. Four lectures were used to prepare the students for the CFD laboratories. At the start of the course, CFD lecture 1, "Introduction to CFD," was presented to prepare students to learn CFD methodology and procedures. The CFD lecture at the intermediate level covers similar topics to those in the introductory level course, but with more details on CFD uncertainty analysis. Three additional CFD lectures were presented to help students learn deeper CFD knowledge, including "Numerical Methods for CFD," "Turbulence Modeling for CFD," and "Grid Generation and Post-processing for CFD." The laboratories for pipe flow, airfoil flow, diffuser flow, and Ahmed car flow were sequential from beginning to end of semester with increasing depth. Unlike the CFD labs at the introductory level, labs at the intermediate level are largely self-guided. However, a short workshop was used to show students the basic procedures and key functions/features of the Educational Interface before CFD Lab 1. Regular office hours were also provided every week to answer students' questions. Detailed exercise notes guide students step-by-step on how to use the Educational Interface to achieve specific objectives for each lab, which is similar to those at the introductory level, but were designed to encourage students' self-learning. CFD lab report instructions (Appendix D) help students step-by-step how to present their results and findings in written and graphical form. Lectures and exercise notes are distributed through the class Web site [30]. CFD concepts covered in pipe, airfoil, diffuser, and Ahmed car exercise notes were developed to meet the learning objectives of course and CFD Labs (Appendix C). The CFD concepts for the pipe flow are those covered in the introductory level pipe flow lecture, and more on iterative error, verification for friction factor and axial velocity profiles, the effect of grid refinement ratio, and validation using EFD. CFD concepts for the airfoil flow module are boundary conditions (inlet, outlet, symmetry, airfoil), effect of domain size, effect of order of accuracy on verification results, validation of pressure coefficient using EFD, manual definition of grid topology, effect of angle of attack, and inviscid vs. viscous modeling. CFD Concepts for the diffuser flow module are grid and iterative convergence, turbulent flow with/without boundary layer separation, streamlines, effect of turbulence models, effect of expansion angle, and validation using EFD. CFD Concepts for the flow over Ahmed car module are mesh and iterative convergence, effect of slant angle, unsteady boundary layer separation with vortex shedding frequency and Strouhal Number analysis, flow animations, and validation using EFD. Student performance is evaluated based on their CFD reports and pre/post-tests. The CFD report is in a similar format to that used in the introductory level report, but with questions that are more difficult. Types of questions in pre- and post-tests are similar to those used at introductory level, but cover more advanced topics in CFD (31 CFD questions), specially focused on CFD uncertainty analysis (verification and validation).

The gas-dynamics and aerodynamics laboratories at Iowa State University are 0.5-semester hour courses required in aerodynamics engineering. Traditionally, laboratories used EFD for highlighting fundamental principles covered in complementary aerodynamics lecture courses for AFD, but were restructured for complementary CFD. The CFD lectures covered theory, Schlieren systems, and CFD methodology and procedures. The nozzle and airfoil flow CFD Educational Interfaces were used. Concepts introduced for the airfoil flow module are streamlines, streaklines, and path lines (AFD) and their connection to flow visualization using CFD and EFD, Bernoulli's equation, and aerodynamic characteristics of an airfoil (lift/drag coefficients vs. angle of attack). Concepts for the gas-dynamics-laboratory course are shock positions within a nozzle, 1st, 2nd and 3rd critical Mach numbers for the nozzle, axisymmetric vs. 2D flows, Mach number, and λ-shock wave patterns.

The senior-level fluid mechanics and heat transfer lab course at Cornell University is required of all students in mechanical and aerospace engineering. Traditionally, the laboratory used EFD only, and was modified to include complementary CFD. The course typically has about 110 students with two professors and six teaching assistants providing instruction. A heated pipe-flow experiment is one of six experiments the students perform during the semester, and this course also places emphasis on the ability of students to express themselves clearly in a technical document, so their lab reports are graded for clarity of expression as well as technical content. The pipe flow CFD Educational Interface was used. Concepts covered are: the CFD process, basic CFD strategy, turbulence modeling, and operating details of the Educational Interface. The Cornell experiment is unique among the pipe-flow experiments described here, in that it studies the effect of heat transfer from the pipe to the flowing gas and CFD is used to predict the development of the thermal boundary layer, as well as velocity profiles, inside the pipe. Comparisons are made with classical correlations and measured values of Nusselt number, as well as the effect of heating on pipe friction factor. Students find the added CFD component to be especially enlightening for this experiment, as they can see visualizations of the velocity and temperature fields inside the pipe—details they cannot observe directly in the experiment, as the pipe wall is solid brass.

The required, junior-level fluids mechanics course in the Mechanical Engineering department at Howard University does not have a formal laboratory component. The thermal-fluids laboratory is required in the second-semester as part of the Applied Thermodynamics course, which is also required. The fluid mechanics course had 25 students and one TA. The CFD section of the course consisted of two lectures devoted to basic CFD concepts and uncertainty analysis, two additional lectures covering the use of FlowLab, and one lecture/demonstration of each template from The University of Iowa. The students were required to do an internal and an external flow computational project that was an expansion of a textbook exercise using the FlowLab templates. The students used the two pipe flow templates and the airfoil templates for these assignments. Their performance was evaluated using their laboratory reports for the CFD analysis and by their performance on exams. The exams also involved a CFD exercise.

IV. Evaluation

Over the three-year period of the ISTUE project, the third party evaluator implemented separate evaluation subprojects for each course at each university.

The evaluation design for this project included both formative and summative focuses. In years 1 and 2, formative purposes were most important, i.e., the primary use of the evaluation information was to investigate ways that the educational components could be improved. For example, at three of the implementation sites (Cornell University, Iowa State University, and University of Iowa), students responded to objective Likert type and supply type items that allowed them to report their ability to learn basic concepts and problem solving skills, the strengths of the teaching and labs as they experienced them, and suggestions for improvement. A number of changes were implemented in response to these suggestions, including more hands-on activities, improved laboratory notes, more tailored and effective assignments, improved teaching modules, and the improved CFD template presented in Figure 2. At two annual meetings of project staff (June 2003 and June 2004), the evaluation team presented detailed reports of this formative evaluation, including analyses of students' scaled and open-ended responses. What follows is a summary of these more detailed formative reports and how they resulted in improvements in the Educational Interface, teaching modules and instructional practices.

A. The University of Iowa

Prior to initiation of the ISTUE project, course evaluation were consistent with the ABET engineering criteria using course outcomes worksheets and assessment reports based on a broad, but limited, number of course objectives (about ten). Assessment techniques used student performance, student surveys administered by the College of Engineering, and faculty observation. As part of the ISTUE project, an additionally detailed evaluation was performed for the introductory level fluid mechanics course for all three years and for the intermediate level course for the last year. For the introductory level course, during the first year, detailed objectives and survey items were developed for lectures (12 objectives and 32 items), problem solving (7 objectives and 27 items), and EFD and CFD (5 objectives and 12 items each) laboratories. The student self-report surveys included demographics, allowed for student comments and suggestions, and were administered by the CEA with independent and anonymous student responses. The complete survey was used during the first and second years.

Student survey data during the first two years indicated that students took the formative evaluation task seriously and that they could contribute good suggestions for improvements. Laboratory reports at both introductory and intermediate levels indicated that students learned the purposes of CFD and design simulation, CFD processes, and data analyses, including verification and validation, and that they developed a deeper knowledge of fundamental CFD concepts. Students' comments in year 1 at the introductory level indicated that they needed "hands-on as much as possible," that it was "difficult to import EFD data and compare with CFD results," and that could benefit from more flexibility on specifying software functions, such as "change of background color in XY plot" and "easier way on gathering and saving figures." Students' comments in year 3 at the same level indicated that they thought, "hands-on part is interesting and helpful," and "data comparison between CFD and EFD is effective for more understanding of fluid mechanics." Intermediate level students' comments in year 3 also provided very positive evaluations, such as "I learned a lot from the labs," "The design of this interface eases the CFD learning," "I am satisfied with the hands-on part," and "The interface will better prepare for industry and my future career." Overall student comments during the past three years indicated that they liked the hands-on, step-by-step approach, appreciated the features of the CFD Educational Interface that allowed flow visualization and comparisons with AFD and EFD features of the CFD Educational Interface and considered valuable the opportunity to learn CFD, which they may use in their future careers. However, they also felt that clearer instructions and a more user-friendly, in-depth, robust, faster interface should be developed, with broader internet accessibility. Students at introductory levels preferred to work in groups, whereas at the intermediate level, they preferred to work individually (one-person one-computer). Faculty opinions based on their observations were consistent with interpretations of students' lab performance and their survey data.

B. Iowa State University

Formative evaluation at Iowa State also relied on students responding to end of course surveys, as presented in Tables 3 and 4. Responses to CFD-related questions indicated that students benefited from the use of FlowLab. Though most students assessed the volume of material covered to be approximately correct, a few students felt that the FlowLab exercises took too long to complete. However, most of the students appreciated having the CFD component in the course and felt that having all three components of fluid flow analysis, i.e., EFD, AFD and CFD, led to better understanding of the course material.

C. Cornell University

Formative evaluation using surveys at Cornell indicated that small groups were well suited to introducing students to CFD basics through the Educational Interface. The FlowLab experience improved students' understanding of the lab through contour and

Question		SA	A	a	d	D	SD	nop
FlowLab is an easy to use CFD tool.	n	1	10	12	3	1	2	0
	%	3	34	41	10	3	7	0
The hands-on aspects of the CFD lab helped me learn valuable skills and knowledge.	n	5	9	10	1	1	2	1
	%	17	31	34	3	3	7	3
CFD taught me things that I could not learn through EFD or AFD alone.	n	1	6	12	4	1	2	3
	%	3	21	41	14	3	7	10
The CFD lab contributed to my understanding of Aerodynamics.	n	4	5	16	2	0	2	0
	%	14	17	55	7	0	7	0
EFD and CFD results from this lab helped my basic understanding of AFD and the underlying theory.	n	1	7	16	1	2	1	1
	%	3	24	55	3	7	3	3
CFD is a useful addition to the EFD lab.	n	4	7	16	0	0	2	0
	%	14	24	55	0	0	7	0
I would recommend the CFD lab to others.	n	2	6	12	3	0	3	3
	%	7	21	41	10	0	10	10
I have used CFD in some form before this class.	n	5	2	2	4	3	12	1
	%	17	7	7	14	10	41	3
As a result of my learning in this course, I have run one or more simulations with FlowLab.	n	9	7	12	1	0	0	0
	%	31	24	41	3	0	0	0
As a result of my learning in this course, I can appreciate the connection between EFD, AFD &CFD.	n	8	10	9	0	1	0	1
	%	28	34	31	0	3	0	3
As a result of my learning in this course, I have a basic understanding of CFD methodology and procedures.	n	3	6	12	5	1	1	1
	%	10	21	41	17	3	3	3

Table 3. Key results from AERO E. 243L survey, Iowa State University. Response scale: Strongly Agree (SA), Moderately Agree (A), Slightly Agree (a), Slightly Disagree (d), Moderately Disagree (D), Strongly Disagree (SD), and No Opinion (nop).

vector plots, and resulted in many students showing an enthusiasm for learning more about CFD.

D. Howard University

An informal self-evaluation at Howard received generally positive responses from students. The most frequent comment was the desire for more time to use the CFD software during the semester.

E. Summative Evaluation and Outcomes Assessment: Overview

By the third year of the project (2004-2005), the formative phase of the evaluation design was completed. The year 3 evaluation focused on documenting student outcomes for the revised and improved implementation of the CFD components, including the Educational Interface. In order to concentrate on documenting outcomes with objective achievement tests, the year 3 evaluation relied on multiple choice and supply-type objective tests of students' knowledge of basic facts, skills, problems and applications related to CFD. The summative evaluation and outcomes assessment took place at The University of Iowa in both introductory and intermediate fluid mechanics courses.

Implementing this summative evaluation required an objective measure of student outcomes in at least one curricular area, and the project staff and evaluation team chose the CFD Educational Interface as applied to undergraduate fluid dynamics curricula. First, the instructional staff wrote and revised a pool of items for each of the two fluid dynamics courses (introductory and intermediate level undergraduates) as described in the previous sections. Representative items from the test for each course are presented in Table 5 and Table 6. Then staff reviewed the items and paired them for equivalency following a Table of Specifications [31]. Items in each pair were randomly assigned to either an A or a B version of the pre-test. The same procedure was followed for both courses using the corresponding item pools. At the time of testing during the first week of classes, students in both classes were randomly assigned to either the A or the B version of the pre-test, which they completed. Later in the semester, after completing the appropriate study of CFD and supporting technology, the students then completed the post-tests, which consisted of both the A and B versions. Thus, all students completed only an A or a B version for the pre-test, but took both the A and the B at post-test.

F. Outcome Data for the Introductory Students

1) Pre/Post Knowledge and Skill Test Outcomes: The most intuitively appealing test of students' knowledge and skill outcomes is whether their post-test scores were significantly higher than their pre-test scores on either the A or the B versions of the pre-tests and post-tests, depending on their random assignment. Table 7 presents the results for the introductory course. Both A and B versions of the tests each contained 10 items.

As can be seen from Table 7, students who took the A version of the pre-test scored on average only about 30 percent correct,

Question		SA	A	a	d	D	SD	nop
FlowLab is an easy to use CFD tool.	n	2	10	11	3	0	3	0
	%	6.90	34.48	37.93	10.34	0	10.34	0
The hands-on aspects of the CFD lab helped me learn valuable skills and knowledge.	n	3	7	12	5	1	1	0
	%	10.34	24.14	41.38	17.24	3.45	3.45	0
CFD taught me things that I could not learn through EFD or AFD alone.	n	2	6	11	6	0	0	4
	%	6.90	20.69	37.93	20.69	0	0	13.79
The CFD lab contributed to my understanding of Aerodynamics.	n	1	11	10	5	0	1	1
	%	3.45	37.93	34.48	17.24	0	3.45	3.45
EFD and CFD results from this lab helped my basic understanding of AFD and the underlying theory.	n	1	9	13	3	1	1	1
	%	3.45	31.03	44.83	10.34	3.45	3.45	3.45
CFD is a useful addition to the EFD lab.	n	6	6	11	4	0	1	1
	%	20.69	20.69	37.93	13.79	0	3.45	3.45
I would recommend the CFD lab to others.	n	3	9	11	4	1	1	0
	%	10.34	31.03	37.93	13.79	3.45	3.45	0
I have used CFD in some form before this class.	n	2	4	9	2	3	8	1
	%	6.90	13.79	31.03	6.90	10.34	27.59	3.45
As a result of my learning in this course, I have run one or more simulations with FlowLab.	n	8	11	7	2	0	0	1
	%	27.59	37.93	24.14	6.90	0	0	3.45
As a result of my learning in this course, I can appreciate the connection between EFD, AFD &CFD.	n	8	12	7	1	0	0	1
	%	27.59	41.38	24.14	3.45	0	0	3.45
As a result of my learning in this course, I have a basic understanding of CFD methodology and procedures.	n	5	14	6	2	0	1	1
	%	17.24	48.28	20.69	6.90	0	3.45	3.45

Table 4. Key results from AERE 311 survey, Iowa State University. Response scale: Strongly Agree (SA), Moderately Agree (A), Slightly Agree (a), Slightly Disagree (d), Moderately Disagree (D), Strongly Disagree (SD), and No Opinion (nop).

probably close to what they would have scored by chance alone. This finding suggests that students did not have the skills or knowledge tested by the quiz prior to instruction. Students responding to the B version scored a little better, approximately 40 percent correct at pre-test, but still not well enough to indicate that they knew much of the information contained on the B version of the pre-test.

The scores on the post-tests were also low and did not indicate much knowledge and skill growth on the tested content. Students who took the B version presented virtually flat performance, correctly answering on average only 38.4 percent of the items on the post-test. Students responding to the A version demonstrated some modest improvement on their post-test, going from about 30 percent correct on the pre-test to 46 percent correct on average on the post-test. However, this growth for the A version students, while statistically significant (t (df = 1, 32) = 4.67, $p < 0.0001$), can not be viewed as much of a success. The expectation was that all students would demonstrate substantial gains and move to 70–75 percent mastery on the post-test items for both A and B versions.

It is also worth noting that all students took both A and B versions at post-test. Students' post-test scores on the not pre-tested items (post-test B for those who had pre-test A and post-test A for those who had pre-test B) are similar to their other scores. Pre-test A students had a mean of 3.94 on the B items at post test, which is not significantly different from the B version pre-test students, whose mean on the post-test was 3.84 (see Table 7). Similarly, pre-test B students had a mean of 4.24 on the A items at post-test, which is only marginally different from the A version pre-test students, whose mean at post-test was 4.61.

Taken by themselves, the post-test items indicate that these introductory students did not demonstrate satisfactory knowledge of this content as sampled by the post-test after instruction in CFD. These items were clearly too difficult for students at both pre-test and post-test.

2) Introductory Students Self Reported Knowledge and Skills: In the current evaluation, introductory students also self-assessed their growth in conceptual knowledge about fluid dynamics, experimental fluid dynamics and computational fluid dynamics on pre and post surveys. Specific items on the survey clustered into factors related to knowledge and skill in each of three clusters.

Table 8 lists the items that constituted the CFD cluster. Students filled out the self-evaluation of their abilities at the beginning of the course and then again at the end, after they had taken the post-test.

As can be seen from the items in Table 8, on the self-reported survey items, students were evaluating their knowledge and skill at a more general level than that measured by the test items. Table 9

1. Which is the correct "CFD Process"?

A. Physics→Geometry→Mesh→Solve→Reports→Post-Processing
B. Geometry→Physics→Mesh→Solve→Reports→Post-Processing
C. Geometry→Mesh→Physics→Solve→Reports→Post-Processing
D. Geometry→Mesh→Physics→Reports→Solve→Post-Processing

2. For viscous flow around airfoil, where is the highest pressure location?

A. Near the trailing edge
B. Near the leading edge where the velocities are zero
C. Somewhere away from the foil surface
D. Somewhere in the wake region of the airfoil

3. Which of the following statements are true in description of the effect of angle of attack (α) on lift (C_L) and drag (C_D) coefficients, if α is less than the stalling angle?

A. When α increases, both C_L and drag C_D will increase.
B. When α increases, both C_L and drag C_D will decrease
C. When α increases, C_L will increase but C_D will decrease
D. When α increases, C_L will decrease but C_D will increase

Table 5. Example test items for the introductory course.

1. About verification using AFD data for axial velocity for laminar pipe flow, which of the following is true on description of effect of grid refinement ratio?

A. Verification results will not be sensitive to grid refinement ratio if the coarse mesh is fine enough to be in the asymptotic range.
B. Verification results will not be sensitive to grid refinement ratio if the fine mesh is coarse enough to be out of the asymptotic range.
C. Verification results will not be sensitive to grid refinement ratio when the ratio is so large that the fine mesh is in the asymptotic range while the coarse mesh is far away from the asymptotic range.
D. Verification results are always sensitive to grid refinement ratio.

2. For turbulent pipe flow, what cause the difference between CFD and EFD?

A. The difference is caused by the errors from numerical, modeling and EFD uncertainties.
B. The difference is caused by the errors from numerical methods.
C. The difference is caused by the EFD uncertainties.
D. The difference is caused by the errors from numerical and EFD uncertainties.

3. By which criterion will you say a CFD simulation has been validated by EFD data?

A. If the difference between CFD and EFD is less than the EFD data uncertainties
B. If the difference between CFD and EFD is less than the CFD data uncertainties
C. If the difference between CFD and EFD is less than the combination of EFD and CFD data uncertainties.
D. If the difference between CFD and EFD is less than the convergence limit.

Table 6. Example test items for the intermediate course.

reports pre- to post- survey mean differences on these survey items. In contrast to their pre- to post-test scores, survey item differences indicated considerable growth pre- to post-survey in knowledge and ability that is both statistically, t (df = 1, 64) = 15.89, $p < 0.0001$, and practically significant. There is a 2.61 average unit difference from pre to post on the 6 point scale (the arithmetic mean of all 12 items) with a standard error of that mean of only plus or minus 0.164.

Thus, while introductory students did not demonstrate much gain on the difficult specific knowledge and skill test pre to post instruction, they did report that they were able to complete general tasks using CFD and the Educational Interface and that they had gained considerable general knowledge pre- to post-survey.

G. Outcomes for the Intermediate Students

Because of concerns that the "hard" outcomes might be too difficult for the introductory students to achieve in such a short time period with relatively little practice and other important learning and skills to achieve in the course, staff also implemented the teaching modules and CFD interface in an intermediate fluid dynamics course. Table 10 presents the outcomes for students in the intermediate course.

As can be seen in Table 10, students randomly assigned to the A (N = 18) and B (N = 19) versions of the pre-test correctly answered about 51 percent (8.22/16) and 40 percent (5.95/15) of the items, respectively, prior to being instructed in the CFD components. However, both groups also demonstrated considerable

Group	Pre A Mean	Pre A SD	Pre B Mean	Pre B SD	Post A Mean	Post A SD	Post B Mean	Post B SD	N
A	2.97	1.61			4.61	1.46	3.94	1.82	33
B			3.97	1.56	4.24	1.37	3.84	1.56	31

Table 7. Mean number of items correct for students in the introductory course.

Survey/Element	Statements
Pre-survey assessment introduction	"Right now, at the beginning of this course, I…"
Post-survey assessment introduction	"Compared to how things were in August, right now, at the end of the course, I…"
Representative item stems*	…have a basic understanding of CFD methodology and procedures. …can use Flowlab for solving laminar and turbulent pipe flow and inviscid and viscous airfoil flow. …can run Flowlab and implement the CFD process for laminar and turbulent pipe flow. …can evaluate grid convergence through analysis of solutions on coarse, medium, and fine grids. …can compare the computational results with the experimental data and analyze the differences. …can related the CFD to fluid physics presentations in written materials and in the classroom lectures.
Likert-type Scale	Strongly Agree = 6, Moderately Agree = 5, Slightly Agree = 4, Slightly Disagree = 3, Moderately Disagree = 2, Strongly Disagree = 1, No Opinion

*There are a total of 12 items measuring reported skill and knowledge growth for CFD.

Table 8. Representative pre- and post-items for the introductory students' surveys.

Pre Mean	Pre SD	Post Mean	Post SD	Difference Mean	Difference SD	N
2.36	1.04	4.97	0.85	2.61	1.31	65

t (df = 1, 64) = 15.89, $p < 0.0001$

Table 9. Pre- compared to post-survey results for introductory students on the CFD self-reported skill items.

growth from pre- to post-test. Those students receiving the A version pre-test answered more than 50 percent more items correctly on the A post-test (Mean = 12.61, SD = 1.2), for a total average correct of almost 80 percent. Those students receiving the B version pre-test answered 75 percent more items correctly on the B post-test (Mean = 10.37, SD = 2.48), for a total average correct of approximately 70 percent correct. These differences are highly statistically significant ($Mean_{diff} = 4.39$, $SD_{diff} = 2.06$, $t(1, 17) = 9.05$, $p < 0.001$) for the A pre-test group as well as for the B pre-test group ($Mean_{diff} = 4.42$, $SD_{diff} = 2.59$, $t(1,18) = 7.44$, $p < 0.0001$) for each respectively). Based on these comparisons, students in the intermediate class demonstrated significant learning outcomes as a result of instruction in the CFD components.

One concern that needs addressing is whether the students simply remembered the items from the pre-test and somehow learned those better during instruction and, thus, did better on the post-test over the same items, even though they may not have learned the outcomes thoroughly. In order to test for this effect of pre-testing [32], Table 10 also compares students' pre- and post-test scores on the two different versions. The randomly assigned students had almost the same post-test scores regardless of which pre-test version they took. In addition students had significantly more items correct on the post-tests, regardless of which pre-test version they took and regardless of the apparent likelihood that the B version had more difficult items, regardless of when it was administered[1]. Students who took pre-test version A scored 51 percent correct on the pre-test and significantly higher on the crossed post-test version B, 72 percent correct ($Mean_{diff} = 2.61$, $SD_{diff} = 3.0$, $t(1,17) = 3.69$, $p < 0.002$). Students who took

[1] Review of the item statistics for the A and B versions suggests that some of the B items were more difficult regardless of whether the A pre-test students or the B pre-test students were answering them. Given an equating sample, it would be possible to equate and slightly adjust the post-test scores on the A and B version to make them more comparable [34]. Then the comparison of scores on the A version of the pre-test with the B version of the post-test and the B version of the pre-test with the A version of the post-test would be more precise. However, since this study is analyzing just one sample and since both groups demonstrated significant gains in spite of lack of precision due to slight differences in the two versions, there is little to be gained by this refinement.

	Pre-A		Pre-B		Post-A		Post-B		
Group	Mean	SD	Mean	SD	Mean	SD	Mean	SD	N
A	8.22	2.43			12.61	1.20	10.83	2.33	18
B			5.95	2.81	12.73	2.23	10.37	2.48	19

Table 10. Mean number of items correct for students in the intermediate course.

Compared to how things were in August, right now, at the end of this course, I:

…have a more thorough understanding of CFD and uncertainty analysis methodology and procedures
…can better use EFD data for validation of CFD results
…have a more thorough understanding of CFD methodology and procedures
...can more competently run FlowLab and implement the CFD process to solve inviscid and viscous (turbulent) airfoil flow
…can better evaluate iterative convergence through setting iterative convergence criteria and analysis of solution residuals
...can better evaluate CFD uncertainty analysis through analysis of solutions of coarse, medium and fine grids
…can more proficiently use FlowLab to manually generate structured meshes for pipe, airfoil, and diffuser.
…can more thoroughly related the CFD to fluid physics presentations in written materials and in the classroom lectures

Table 11. Intermediate students survey items.

pre-test version B scored on average 40 percent correct at pre-test and almost 80 percent correct on the A version post-test ($Mean_{diff}$ = 6.78, SD_{diff} = 3.02, $t\,(1,18) = 9.8$, $p < 0.0001$). It is worth emphasizing that these effect sizes are substantial and represent substantial outcomes in intermediate students' knowledge and skill as measured by these test items.

H. Intermediate Students Survey Outcomes

Intermediate students also completed survey items. However, their survey was administered only after the post-test, and was in a retrospective format [33]. Table 11 presents a sample of the items from the survey.

In general, intermediate students agreed with these statements, M = 4.79, SD = 0.67, n = 37 (Strongly Agree = 6, Strongly Disagree = 1) at about the same strength as the students in the introductory course (Table 9). Thus one can conclude that intermediate students also viewed themselves as benefiting at the level of conceptual understanding, skill growth, and comfort with CFD through their experiences with the Educational Interface.

I. Conclusions and Discussion

Results from surveys of the students in two different levels of courses with a well-developed CFD Educational Interface as implemented in introductory and intermediate fluid dynamics courses suggests strongly that on average students reported substantial learning of general outcomes, such as comfort with CFD, being able to analyze solutions with coarse, medium and fine grids, and proficient use of FlowLab to manually generate structured meshes for pipe, airfoil, and diffuser models. It seems clear from the data presented here that students, even with relatively brief exposures in their introductory and intermediate classes become more aware of CFD and how it relates to experiments and general and specific fluid dynamics theory and practice.

The results from the introductory course suggest that many students at this level are unable, after a relatively brief exposure with limited practice, to fully understand the more sophisticated CFD concepts and apply them to demanding word problems in a test situation. However, in the intermediate course, students on average did show considerable growth in their sophisticated understanding and application of CFD principles to conceptual and applied problems.

The general conclusion is that this implementation of CFD (FlowLab) has resulted in students' gaining important practical and theoretic knowledge about aspects of fluid dynamics and how they are modeled in the CFD, conceptual and EFD frameworks they are learning.

Future studies should investigate the trade-offs in terms of improved student understanding of fundamental principles with the CFD included versus not included in otherwise similar fluid dynamics courses at both the introductory and intermediate level. The Educational Interface as described above has demonstrated its effectiveness in the context of these two courses at differing levels. One can now suggest that its applicability be further investigated to specify how and in which conditions it can be used most efficiently and effectively.

V. Conclusions and Future Work

The project has been successful in developing a CFD Educational Interface for pipe flow, with and without heat transfer; nozzle flow with shock waves; diffuser and airfoil flows; and the Ahmed car flow with unsteady separation. The interface introduces features that effectively match students' learning needs. The interface design provides students with hands-on experience, gained through an interactive and user-friendly environment, and encourages students' self-learning. The implementation has improved over time and has been judged successful by students, based on site testing at partner universities with different learning objectives, courses or laboratories, applications, conditions, exercise notes, and evaluations. The CFD Educational Interface has been proven to be an effective and efficient tool to help students learn CFD methodology and procedures following the CFD process, and as a useful training vehicle to prepare students for using CFD in their future careers in industry. The developed prototype of The Educational Interface provides a solid base for developing more effective and more efficient next generation CFD educational software. Both on-site and independent CEA evaluations showed that significant progress was made in training CFD expert users at the intermediate level fluid mechanics course, and partially successful in training CFD novice users at the introductory level undergraduate fluids mechanics course. The teaching modules developed by the ISTUE team have been disseminated by Fluent.

The results of the present study enable the authors to address issues posed in the introduction:

1. Both introductory and intermediate level students like "hands-on" experience. However, for the students at the intermediate level, a hands-on and self-discovery oriented approach is preferred over demonstration. This is probably due to their deeper background and knowledge of CFD, and relative to novice students, their desire to learn by themselves.
2. Comparisons made while using FLUENT, unmodified FlowLab, and the CFD Educational Interface indicated that CFD can, in fact, detract from the development of a deeper knowledge of fundamental fluid mechanics concepts if the software interface and the accompanying curriculum materials are not carefully designed. An interface that provides too many options extraneous to the application at hand can confuse students. In this study, it was observed that confusion can be reduced by the development of appropriate teaching modules, but the authors' further purpose that a more optimal solution exists through the use of an Educational Interface in conjunction with well thought out supporting materials. Ideally, the Educational Interface would allow a student to define a geometry, specify physics options, mesh the domain, converge results, and conduct post-processing, all within the same interface without the need to move from one application to another, such as from a pre-processor to a solver or post-processing application.
3. To use a generalized CFD Educational Interface with complementary teaching module materials will be necessary for students to avoid the perception of CFD as a black box and promote a detailed understanding of CFD methodology and procedures. Students learning outcomes will be enhanced through a series of CFD labs which cover different varying depths and options of the same interface.
4. The authors realize that the correct selection of an educational CFD software package will most likely depend on students' backgrounds and their CFD knowledge. For introductory and intermediate undergraduate level students, to use a specialized educational software package, such as the one developed in this study, seems to be the optimal choice. Further development of this CFD Educational Interface, while allowing for an even greater depth of options will facilitate the interface's use by advanced level and expert users, and may possibly replace commercial CFD software in the future for educational activities similar to that performed in the current study.
5. The authors attribute the steep learning curve associated with industrial CFD tools to the lack of a structured learning interface. The ideal CFD educational software seems to have a generalized interface and a different level of depth for different levels of users, allows for hands-on access, and possesses all other features that the current CFD Educational Interface has (section II B).
6. The best approach for introductory level undergraduate students is to focus on overall CFD process and flow visualizations, and to use CFD as a tool to help students understand the fundamental fluid mechanics concepts related to fluid physics and classroom lectures, with the aid of complementary EFD/UA labs. The best approach for intermediate level undergraduate students is to practice a deeper and broader range of CFD methodology and procedures, including numerical methods, modeling, uncertainty analysis, and to encourage students' self-learning with the aid of exercise notes and a series of CFD lectures. The best approach for an intermediate or advanced graduate level course may be to focus on CFD code development.
7. Lecture and laboratory course teaching is more suitable for introductory level undergraduate students who do not have a good background of CFD knowledge. For intermediate undergraduate/graduate level students, studio and multimedia models seem to be more appropriate since students at this level prefer to work, think, and learn alone with help from TAs and lab instructions.
8. Traditionally, CFD curriculum has focused on code development while not training expert users, as attempted in the current study. In traditional approaches, students are asked to either partly or completely develop their own CFD research code using the CFD theory they learned. The authors think the approaches described in the current study are the best way to train expert CFD users. It may be best to use a combination of both approaches to teach CFD, with different weights for different levels of students. The primary objective can shift from training expert users for introductory or intermediate level undergraduate students to CFD code development for the introductory/intermediate graduate level students.

The present study has made significant progress on enlightening educators regarding many of the issues discussed herein; however, more experience is needed, especially to develop a better understanding of issues 6, 7, and 8.

There are still many ways to improve the CFD Educational Interface and its implementation. Analysis of the pre/post-tests and teaching modules showed that the partially successful implementation of the Educational Interface in introductory level undergraduate classes may be attributed to: (1) some CFD concepts and questions were too difficult, such as those pertaining to verification and validation; and (2) CFD lab exercise notes did not exactly match the CFD concepts/questions in the pre/post-tests. Site testing validated the versatility of the CFD Educational Interface, since courses and pedagogy differed at the collaborative universities involved in the present study. This versatility suggests an even wider applicability of the CFD Educational Interface at diverse universities for inter and multi disciplinary use, and this could serve as a model for other simulation technologies.

Future work will focus on: (1) developing a further improved user interface having a dynamic sketch window to facilitate import and export of data, reports (convergence histories, separate monitoring convergence from diagnostics results), diagnostic capabilities and graphics, including verification and validation, and increased versatility for grid generation; (2) for introductory level undergraduate courses, redesign the pre/post-test questions removing advanced CFD concepts, and improve CFD lab exercise notes to be more closely linked to pre/post-test questions and to better meet the CFD lab objectives; (3) developing extensions for more general applications, including CFD templates for inter- (e.g., chemical engineering) and multi- (e.g., physics) disciplinary applications appropriate for national dissemination that facilitate modeling steady and unsteady 2D internal (pipe, diffuser, nozzle, transition, noncircular cross section) and external (airfoil, car, cylinder) flow at low and high speed, heat transfer, etc. conditions; (4) developing extensions that facilitate further student self-learning; (5) providing remote access to the Educational Interface via college computer labs and the Internet; and (6) implementing these improvements with site testing and evaluation. Ideally, future generations of CFD Educational Interfaces will be closely tied to expert-user industrial software interfaces.

Acknowledgments

This research was funded by National Science Foundation Course, Curriculum and Laboratory Improvement - Educational Materials Development Program Award #0126589 under the administration of Dr. R. Seals. We would like to thank Prof. Elizabeth Fisher for her input and help in implementing the pipe flow template at Cornell University. IIHR staff member Mark Wilson provided computer support.

References

[1] Merino, D., and Abel, K.D., "Evaluating the Effectiveness of Computer Tutorials Versus Traditional Lecturing in Accounting Topics," *Journal of Engineering Education*, Vol. 92, No. 2, 2003, pp. 189–194.

[2] Diefes-Dux, H.A., Samant, C., Johnson, T.E., and O'Connor, D., "Kirkpatrick's Level 1 Evaluation of the Implementation of a Computer-Aided Process Design Tool in a Senior-Level Engineering Course," *Journal of Engineering Education*, Vol. 93, No. 4, 2004, pp. 321–331.

[3] Avouris, N.M., Tselios, N., and Tatakis, E.C., "Development and Evaluation of a Computer-Based Laboratory Teaching Tool," *Computer Applications in Engineering Education*, Vol. 9, Issue 1, 2001, pp. 8–19.

[4] Regan, M., and Sheppard, S., "Interactive Multimedia Courseware and the Hands-on Learning Experience: An Assessment Study," *Journal of Engineering Education*, Vol. 85, No. 2, 1996, pp. 123–131.

[5] El-Bibany, H., "Multimedia Development Software: Object-Oriented Interface-Based Simulation," *Journal of Computing in Civil Engineering*, Vol. 10, Issue 4, 1996, pp. 295–299.

[6] Kirkpatrick, A., and Willson, B., "Computation and Experimentation on the Web with Application to Internal Combustion Engines," *Journal of Engineering Education*, Vol. 87, Supplemental 1998, pp. 529–537.

[7] Mackenzie, J.G., Earl, W.B., Allen, R.M., and Gilmour, I.A., "Amoco Computer Simulation in Chemical Engineering Education," *Journal of Engineering Education*, Vol. 90, No. 3, 2001, pp. 331–345.

[8] Campbell, J.O., Bourne, J.R., Mosterman, P.J., and Brodersen, A.J., "The Effectiveness of Learning Simulations for Electronic Laboratories," *Journal of Engineering Education*, Vol. 91, No. 1, 2002, pp. 81–87.

[9] Wiesner, T.F., and Lan, W., "Comparison of Student Learning in Physical and Simulated Unit Operations Experiments," *Journal of Engineering Education*, Vol. 93, No. 3, 2004, pp. 195–204.

[10] Wankat, P.C., "Integrating the Use of Commercial Simulators into Lecture Courses," *Journal of Engineering Education*, Vol. 91, No. 1, 2002, pp. 19–23.

[11] Hoorfar, M., Najjaran, H., and Cleghorn, W.L., "Simulation and Animation of Mechanical Systems to Enhance Student Learning," *Computers in Education Journal*, Vol. 13, No. 1, 2003, pp. 39–44.

[12] Adjouadi, M., and Ayala, M., "Introducing Neural Studio: An Artificial Neural Networks Simulator for Educational Purposes," *Computers in Education Journal*, Vol. 14, No. 3, 2004, pp. 33–40.

[13] Briley, W.R., and Hodge, B.K., "CFD Project Combining Solution Algorithms, Software Development/Validation, and Viscous Flow Calculations," *Computer Applications in Engineering Education*, Vol. 5, Issue 3, 1997, pp. 161–168.

[14] Pieritz, R.A., Mendes, R., Da Silva, R.F.A.F., and Maliska, C.R., "CFD Sinflow Library: A Framework to Develop Engineering Educational Codes in CFD and Thermal Sciences," *Computer Applications in Engineering Education*, Vol.12, Issue. 1, 2004, pp. 31–43.

[15] Pieritz, R.A., Mendes, R., Da Silva, R.F.A.F., and Maliska, C.R., "CFD Studio: An Educational Software Package for CFD Analysis and Design," *Computer Applications in Engineering Education*, Vol. 12, Issue 1, 2004, pp. 20–30.

[16] Henderson, B.S., Navaz, H.K., and Berg, R.M., "A New Approach to Teaching Compressible Flow," *(Web) Proceedings, 1999 ASEE Annual Conference and Exposition, www.asee.org/acPapers/99conf382.pdf.*

[17] Aung, K., "Design and implementation of an Undergraduate Computational Fluid Dynamics (CFD) Course," *(Web) Proceedings, 2003 ASEE Annual Conference and Exposition, www.asee.org/acPapers/2003-24_Final.pdf.*

[18] Guessous, L., "Incorporating Matlab and FLUENT in an Introductory Computational Fluid Dynamics Course," *Computers in Education Journal*, Vol. 14, No. 1, 2004, pp. 82–91.

[19] Olinger, D.J., and Hermanson, J.C., "Integrated Thermal-Fluid Experiments in WPI's Discovery Classroom," *Journal of Engineering Education*, Vol. 91, No. 2, 2002, pp. 239–243.

[20] Homsy, G.M., "Multi-Media Fluid Mechanics," *(Web) Proceedings, 2001 ASEE Annual Conference and Exposition, www.asee.org/acPapers/00709_2001.pdf.*

[21] Ribando, R.J., Scott, T.C., and O'Leary, G.W., "Application of the Studio Model to Teaching Heat Transfer," *(Web) Proceedings, 2001 ASEE Annual Conference and Exposition, www.asee.org/acPapers/00035_2001.pdf.*

[22] Caughey, D.A., and Liggett, J.A., "A Computer-Based Textbook for Introductory Fluid Mechanics," *(Web) Proceedings, 1998*

ASEE Annual Conference and Exposition, www.asee.org/acPapers/00074.pdf.

[23] Niewoehner, R., and Filbey, J., "Using the TetrUSS CFD Suite in Undergraduate Research," *(Web) Proceedings, 2000 ASEE Annual Conference and Exposition, www.asee.org/acPapers/20677.pdf.*

[24] Hailey, C.E., and Spall, R.E., "An Introduction of CFD into the Undergraduate Engineering Program," *(Web) Proceedings, 2000 ASEE Annual Conference and Exposition, www.asee.org/acPapers/20368.pdf.*

[25] Navaz, H.K., Henderson, B.S., and Mukkilmarudhur, R.G., "Bring Research and New Technology into the Undergraduate Curriculum: A Course in Computational Fluid Dynamics," *(Web) Proceedings, 1998 ASEE Annual Conference and Exposition, www.asee.org/acPapers/00043.pdf.*

[26] Young, J.H, and Lasher, W.C., "Use of Computational Fluid Dynamics in an Undergraduate ME Curriculum," *ASME FED-Vol. 220, Instructional Fluid Dynamics*, 1995, pp. 79–82.

[27] Guessous, L., Bozinoski, R., Kouba, R., and Woodward, D., "Combining Experiments with Numerical Simulations in the Teaching of Computational Fluid Dynamics," *(Web) Proceedings, 2003 ASEE Annual Conference and Exposition, www.asee.org/acPapers/2003-603_Final.pdf.*

[28] *flowlab.fluent.com/collaborations/nsf/.*

[29] *css.engineering.uiowa.edu/~fluids.*

[30] *css.engineering.uiowa.edu/~me_160.*

[31] Linn, R.L., and Gronland, N.E., *Measurement and Assessment in Teaching*, 8th ed., Upper Saddle River, N.J.: Merrill, 2000.

[32] Shadish, W., Cook, T., and Campbell, D., *Experimental and Quasi-experimental Designs for Generalized Causal Inferences*, Boston, Mass.: Houghton Mifflin, 2002.

[33] Lam, T., and Bengo, P., "A Comparison of Three Retrospective Self-reporting Methods of Measuring Change in Instructional Practice," *American Journal of Evaluation*, Vol. 24, No. 1, 2003, pp. 65–80.

[34] Peterson, N.J., Kolen, M.J., and Hoover, H.D., "Scaling, Norming, and Equating," in Educational Measurement (3rd ed.), Linn, R. (ed), Phoenix, Ariz.: Oryx Press, 1993.

Authors' Biographies

Frederick Stern is a professor of mechanical engineering with 20+ years experience in teaching undergraduate and graduate courses in the mechanical engineering curriculum. Research interests are modeling, CFD code development, towing tank experiments, and uncertainty analysis all in support development simulation based design for ship hydrodynamics.

Address: IIHR-Hydroscience & Engineering, The University of Iowa, C. Maxwell Stanley Hydraulics Laboratory, Iowa City, Iowa 52242-1585; telephone: (+1) 319.335.5215; fax: (+1) 319.335.5238; e-mail: frederick-stern@uiowa.edu.

Tao Xing is an assistant research scientist at the C. Maxwell Stanley hydraulic laboratory, The University of Iowa. He received his Ph.D. in Mechanical Engineering from Purdue University, 2002.

Address: IIHR-Hydroscience & Engineering, The University of Iowa, C. Maxwell Stanley Hydraulics Laboratory, Iowa City, Iowa 52242-1585; telephone: (+1) 319.335.6293; fax: (+1) 319.335.5238; e-mail: tao-xing@uiowa.edu.

Donald B. Yarbrough is Director of the Center for Evaluation and Assessment and an associate professor of Educational Measurement and Evaluation in the University of Iowa College of Education. He received his Ph.D. in Educational Psychology for the University of Georgia, 1982. His most recent research focuses on program evaluation methodology and the development and use of evaluation standards.

Address: Center for Evaluation and Assessment, 210 Lindquist Center South, The University of Iowa, Iowa City, Iowa 52242; telephone: (+1) 319.335.5567; fax: (+1) 319.384.0505; e-mail: d-yarbrough@uiowa.edu.

Alric Rothmayer is a professor of aerospace engineering and engineering mechanics with 17 years experience in teaching undergraduate and graduate courses in aerospace engineering. His research interests include viscous flow, computational fluid dynamics, asymptotic methods and boundary layer theory, and aircraft icing.

Address: Department of Aerospace Engineering, 2271 Howe Hall, Room 2235, Iowa State University, Ames, Iowa 50011-2271; telephone: (+1) 515.294.8851; fax: (+1) 515.294.3262; e-mail: roth@iastate.edu.

Ganesh Rajagopalan is a professor of aerospace engineering with twenty years of experience in teaching. He has developed a number of undergraduate courses with emphasis on integrating experimental techniques with theory. Dr. Rajagopalan's research emphasis has centered on computationally efficient techniques to study the flow field and operational characteristics of rotating machines such as helicopter rotors.

Address: Department of Aerospace Engineering, 2271 Howe Hall, Room 2233, Iowa State University, Ames, Iowa 50011-2271; telephone: (+1) 515.294.6796; fax: (+1) 515.294.3262; e-mail: rajagopa@iastate.edu.

Shourya Prakash Otta is currently a graduate student in Department of Aerospace Engineering. He graduated from Indian Institute of Technology—Kanpur, India with Bachelor of Technology in Aerospace Engineering in 2000. He worked with Matrix CFD Solutions (a subsidiary of ICEM CFD Engineering) in India from 2000 to 2003.

Address: Department of Aerospace Engineering, 2232 Howe Hall, Iowa State University, Ames, Iowa 50011-2271; telephone: (+1) 515.294.8245; fax: (+1) 515.294.3262; e-mail: shourya@iastate.edu.

David A. Caughey is a professor in the Sibley School of mechanical and aerospace engineering at Cornell University. He has more than 30 years research experience in developing CFD algorithms, most recently applied to turbulent, reacting flows. He and Professor James A. Liggett co-authored the first interactive text book for introductory fluid mechanics.

Address: 248 Upson Hall, Cornell University, Ithaca, New York 14853; telephone: (+1) 607.255.3372; fax: (+1) 607.255.1222; e-mail: dac5@cornell.edu.

Rajesh Bhaskaran is Director of Swanson Engineering Simulation Program in the Sibley School of Mechanical and Aerospace Engineering at Cornell University. He is leading efforts in the Sibley

School to integrate contemporary simulation technologies into the mechanical and aerospace engineering curriculum. He received a Ph.D. in Aerospace Engineering from Iowa State University in 1996.

Address: 284C Grumman Hall, Ithaca, New York 14853; telephone: (+1) 607.255.0390; fax: (+1) 607.255.1222; rb88@cornell.edu.

Sonya T. Smith is a professor in the mechanical engineering department at Howard University and the Director of the Computer Learning and Design Center (CLDC) in the College of Engineering, Architecture, and Computer Sciences. Her research interests are in the areas of CFD applied to aerodynamic applications. She received her Ph.D. in Mechanical and Aerospace Engineering from the University of Virginia in 1995.

Address: Department of Mechanical Engineering, School of Engineering and Computer Science, Howard University, 2300 6th Street, NW, Washington, DC 20059; telephone: (+1) 202.806.4837; fax: (+1) 202.806.5258; e-mail: sts6f@vortex.eng.howard.edu.

Barbara J. Hutchings is currently the Director of Strategic Partnership at Fluent, the leading commercial supplier of CFD software. Barbara joined Fluent at its inception in 1983, after graduating from the Thayer School of Engineering at Dartmouth College with an M.S. degree. She has been working in the field of applied CFD for 20 years and has an active interest in the use of software tools for engineering education.

Address: Fluent Inc., 10 Cavendish Court, Lebanon, New Hampshire 03766; telephone: (+1) 603.643.2600 ext. 312; fax: (+1) 603.643.3967; e-mail: bjh@fluent.com.

Shane Moeykens received his Ph.D. in Mechanical Engineering from Iowa State University in 1994. He is the University Program Manager at Fluent Inc. as well as the FlowLab Product Manager.

Address: Fluent Inc., 10 Cavendish Court, Lebanon, New Hampshire 03766; telephone: (+1) 603.643.2600 ext. 307; fax: (+1) 603.643.3967; e-mail: sam@fluent.com.

Appendices

Appendix A. Course and EFD, CFD Lab Objectives for Introductory Undergraduate Students at The University of Iowa

1. Students in general will enjoy their learning experience in this course.
2. Experimental fluid dynamics (EFD), computational fluid dynamics (CFD), and uncertainty analysis (UA) classroom and pre-lab lectures will effectively prepare students for "hand-on" laboratory experience.
3. "Hands-on" laboratory experience will use EFD, CFD, and UA, as engineering tools in a meaningful learning experience.
4. "Hands-on" laboratory experience will mirror as much as possible "real-life" engineering practice.
5. The lab content and skill development will effectively match students' learning needs, including prior knowledge and skill, student objectives for self development as engineers, and student dispositions and learning styles.
6. Students' evaluation through homework, tests, and pre-lab and laboratory reports will be fair, accurate, proper, feasible, and useful.
7. Evaluations in this course will allow students to show what they know and can do, as related to expected course outcomes.
8. The Web site will be useful for learning in this course, including posting class information, news, schedule, lecture notes, EFD/CFD lab materials, homework and test solutions, grades, image gallery, and links.

Problem Solving

1. Students will be able to apply the definitions of a fluid and shear stress for solving engineering problems, including use of definitions, tables, and graphs of fluid properties such as density, specific weight and gravity, viscosity, surface tension, compressibility, and vapor pressure.
2. Students will be able to apply the definition of pressure and principles and methods used to solve engineering problems for static fluids.
3. Students will be able to apply the principles and methods used to solve engineering problems with fluids in motion, including definitions and calculation of velocity, volume flow rate, acceleration, and vorticity; and pressure variation for rigid body translation and rotation and Bernoulli equation.
4. Students will be able to apply control volume and differential approaches for the continuity, momentum, and energy equations for solving engineering problems.
5. Students will be able to apply the basic concepts of dimensional analysis and similarity for solving engineering problems, including dimensional homogeneity, Buckingham Pi theorem, definitions and uses of important dimensionless parameters, and similarity, scaling laws, and model testing.
6. Students will be able to apply the concepts and calculation methods for external flows for solving engineering problems, including boundary layer theory and definitions of shear stress and force, velocity profile, and boundary layer thickness for laminar and turbulent flow; use of drag coefficients for calculation of drag for bluff bodes; and use of lift and drag coefficients for calculation of lift and drag of airfoils.
7. Students will be able to apply the concepts and calculation methods for internal flows for solving engineering problems, including friction and minor losses for laminar and turbulent smooth and rough pipe flow.

EFD/CFD and UA Labs General

1. Students will have "hands-on" experience with use of complementary EFD and CFD, including modern EFD, CFD, and UA methods and procedures, validate, analyze, and relate results to fluid physics and classroom lectures, and teamwork and presentation of results in written and graphical form.

EFD/UA Labs

1. Provide students with "hands-on" experience with EFD methodology and UA procedures through step-by-step approach following EFD process: setup facility, install model, setup equipment, setup data acquisition using labview, perform calibrations, data analysis and reduction, UA, and comparison with CFD and/or AFD results.
2. Students will be able to conduct fluids engineering experiments using tabletop and modern facilities such as pipe stands and wind tunnels and modern measurement systems, including pressure transducers, pitot probes, load cells, and computer data acquisition systems (labview) and data reduction.
3. Students will be able to implement EFD UA for practical engineering experiments.
4. Students will be able to use EFD data for validation of CFD and Analytical Fluid Dynamics (AFD) results.
5. Students will be able to analyze and relate EFD results to fluid physics and classroom lectures, including teamwork and presentation of results in written and graphical form.

CFD/UA Labs

1. Provide students with "hands-on" experience with CFD methodology (modeling and numerical methods) and procedures through step-by-step approach following CFD process: geometry, physics, mesh, solve, reports, and post-processing.
2. Help students to learn CFD methodology and procedures through the Educational Interface.
3. Students will be able to apply CFD process through use of Educational Interface for commercial industrial software to analyze practical engineering problems.
4. Students will be able to conduct numerical uncertainty analysis through iterative and grid convergence studies.
5. Students will be able to validate their computational results with EFD data from their complementary experimental laboratories.
6. Students will be able to setup IBVP through the Educational Interface, including (1). Create geometry, (2). Setup appropriate fluid properties, viscous model, boundary conditions, and initial conditions, (3). Generate mesh, either automatically by the Educational Interface or manually by

students, (4). Setup appropriate solvers with numerical parameters, (5). Report integral variables and use XY plots, (6). Use contour, streamlines and vectors to examine flow field.
7. Students will be able to learn more flow physics beyond the conditions you used in the complementary EFD labs. Students will conduct parametric studies using the Educational Interface to investigate inviscid vs. viscous flows, effect of turbulent models, effect of angle of attacks, and effect of order of accuracies, etc.
8. Students will be able to analyze and relate CFD results to fluid physics and classroom lectures, including teamwork and presentation of results in written and graphical form.

Appendix B. Instructions and Grading for CFD Lab Report for Introductory Under-Graduate Students at The University of Iowa

Section		Points
PreLab Questions	Submitted before PreLab	10
1. **Title Page**		5
1.1 Course Name		
1.2 Title of report		
1.3 Submitted to "Instructor's name"		
1.4 Your name (with e-mail address)		
1.5 Your affiliation (group, section, department)		
1.6 Date and time lab conducted		
2. **Test and Simulation Design**		10
Purposes of CFD simulation		
3. **CFD Process**		10
Describe in your own words how you implemented CFD process		
(Hint: CFD process block diagram)		
4. **Data Analysis and Discussion (CFD)**		50
Answer questions given in **Exercise Notes** of the CFD lab handouts		
5. **Conclusions**		15
Conclusions regarding achieving the purposes of experiment and simulation		
Describe what you learned from CFD		
Describe your "hands-on" experience		
Describe the cooperation between the group members, if you have.		
Suggestions and improvements		Total 100

Additional Instructions:
1. Each student is required to hand in individual lab report and PreLab questions.
2. Conventions for graphical presentation:
   *CFD figures should be plotted using symbols without X and Y grid
   *All figures in the report should be either the hardcopies of FlowLab or the plots using other commercial software (Excel).
   *Color print of figures recommended but not required
3. Reports will not be graded unless section 1 is included and complete

Appendix C. Course and CFD Lab Objectives for Intermediate Level Students at The University of Iowa

Course Objectives
1. Students will have a working knowledge of basic fluid mechanics definitions, properties, and hydrostatics.
2. Student will learn how to select finite control volumes and apply mass, momentum, angular momentum and energy conservation integral analysis equations to solve a wide variety of fluid flow problems.
3. Student will understand the derivation of differential fluid mechanics equations for conservation of mass, momentum and energy along with appropriate boundary conditions and be able to solve them for many fluid flow problems for which exact solution exist.
4. Student will learn how to simplify the Navier-Stokes equations for Stokes flow, boundary layers, and free shear flows and solve the simplified equations for a wide variety of fluid flow problems.
5. Student will learn how to the apply dimensional analysis and similitude for a wide variety of fluid flow problems.
6. Students will learn the basic concepts and theory of stability, transition, and turbulence, including statistical analysis and averaging, Reynolds-averaged Navier-Stokes equations and turbulence modeling.
7. Student will have a working knowledge of solution of wide variety of fluid flow problems for internal, external, and free shear flows, including laminar and turbulent flows, effects of roughness, pressure gradients and separation, and lift and drag.
8. Students will learn the basics of potential flow theory (basic solutions, complex variables, boundary element methods) and its application to simple flows as well as its limitations.

CFD and UA Labs General
1. Students will have "hands-on" experience with use of complementary CFD and EFD, including modern CFD and UA methods and procedures, validate, analyze, and relate results to fluid physics and classroom lectures, and self-learning and presentation of results in written and graphical form.

CFD/UA Labs
1. Provide students with "hands-on" experience with CFD methodology (modeling and numerical methods) and procedures through step-by-step approach following CFD process: geometry, physics, mesh, solve, reports, and post processing.
2. Help students to run CFD software from novice to professional, so they can run industrial commercial software directly after the CFD/UA labs.
3. Students will be able to apply CFD process through use of Educational Interface to be prepared for use commercial industrial software directly to analyze practical engineering problems.
4. Provide students with experience on setting up IBVP using Educational Interface to solve practical engineering applications.

5. Students will be able to conduct detailed verification and validation analysis through iterative and grid convergence studies, through the interface and hand-calculations.
6. Students will have experiences with internal flow (pipe), external flow (airfoil), steady flow with/without separation (diffuser) and unsteady flow with separation (Ahmed car).
7. Students will be able to investigate more flow physics through parametric studies, such as laminar vs. turbulence (pipe), effect of angle of attack (airfoil), effect of numerical scheme (airfoil), separation vs. non-separation (diffuser), effect of turbulent models (diffuser), effect of slant angles (Ahmed car), and generations of different types of meshes (structured or unstructured).
8. Students will be able to analyze and relate CFD results to fluid physics and classroom lectures, including self-learning and presentation of results in written and graphical form.

APPENDIX D. INSTRUCTION AND GRADING FOR CFD LAB REPORT FOR INTERMEDIATE LEVEL STUDENTS AT THE UNIVERSITY OF IOWA

Section	Points
1. **Title Page**	5
1.1 Course Name	
1.2 Title of report	
1.3 Submitted to "Instructor's name"	
1.4 Your name (with e-mail address)	
1.5 Your affiliation (group, section, department)	
1.6 Date and time lab conducted	
2. **Test and Simulation Design**	10
Purpose of CFD simulation	
3. **CFD Process**	20
Describe in your own words how you implemented CFD process	
(Hint: CFD process block diagram)	
4. **Data Analysis and Discussion**	45
Answer questions given in **Exercises** of the CFD lab handouts	
5. **Conclusions**	20
Conclusions regarding achieving purpose of simulation	
Describe what you learned from CFD	
Describe the "hands-on" part	
Describe future work and any improvements	Total 100

Additional Instructions:

1. Each student is required to hand in individual lab report.
2. Conventions for graphical presentation (CFD):
   *Both experimental data and CFD predictions should be plotted using symbols without X and Y grid
   *To save FlowLab figures, you can either hardcopy using "Alt+print Screen"or use the "hardcopy" function in XY plots.
   *Color print of figures recommended but not required
3. Reports will not be graded unless section 1 is included and complete