Development of *Hands-On* CFD Educational Interface for Undergraduate Engineering Courses and Laboratories

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Abstract

Development described of an educational interface for *hands-on* student experience with computational fluid dynamics (CFD) for undergraduate engineering courses and laboratories. Project part of a three-year National Science Foundation sponsored Course, Curriculum and Laboratory Improvement - Educational Materials Development project with faculty partners from colleges of engineering at Iowa, Iowa State, Cornell and Howard universities along with industrial (commercial CFD code) partner FLUENT Inc, including complementary experimental fluid dynamics and uncertainty analysis. The design of the educational interface teaches students CFD methodology (modeling and numerical methods) and procedures through interactive implementation that automates the CFD process following a step-by-step approach. The CFD process mirrors actual engineering practice: geometry, physics, mesh, solve, reports, and post processing. Predefined active options for students' exercises use a hierarchical system both for introductory and advanced levels and encourages individual investigation and learning. Ideally, transition for students would be easy from advanced level to using FLUENT or other industrial CFD code directly. Generalizations of CFD templates for pipe, nozzle, and airfoil flows facilitate their use at different universities with different applications, conditions, and exercise notes. Implementation based on results from site testing at faculty partner universities for an introductory fluid mechanics course at Iowa, for aerodynamics and gas dynamics laboratory courses at Iowa State, for a required fluid mechanics sequence at Cornell, and for an aerodynamics course at Howard. The evaluation and research plan (created in collaboration with a third party program evaluation center at the University of Iowa) is described, which focuses on exact descriptions of the implementations of the new interface at partner sites, especially as experienced by the students, including preliminary data on immediate student outcomes as documented from site testing for Fall 2003. Also discussed are conclusions and future work.

Introduction

As simulation based design and ultimately virtual reality become increasingly important in engineering practice, it becomes equally important to integrate simulation technology into the undergraduate engineering curriculum. Simulation technology covers a broad range from computerized systems to computerized solutions of engineering problem formulations using mathematical physics modeling, numerical methods, and high performance computing; all of which broadly influences all engineering disciplines. Pedagogy of integration of simulation technology into the undergraduate engineering curriculum and pedagogy of computer-assisted learning are related. The latter includes web-based teaching, CDROM, robotics, studio arts, remote experiments, and computer-based textbooks. Of present interest is integration of computational fluid dynamics (CFD) into undergraduate engineering courses and laboratories. CFD is a widely used tool in fluids engineering with many specialty and commercial CFD codes through out the world covering many application areas. One major obstacle to the greater use of CFD is lack of trained users.

Fluid mechanics courses are included in the curricula of most engineering programs, with both program required and technical elective courses. Program required courses are at both the introductory and advanced levels, whereas technical elective courses are at advanced levels. More than one program often requires introductory level courses (e.g., mechanical, civil, and bio engineering departments) or combined with related subjects such as thermodynamics, heat transfer, and chemical and aerospace engineering. Most introductory courses are textbook based with emphasis on analytical fluid dynamics (AFD) and problem solving with or without experimental fluid dynamics (EFD). EFD used primarily to demonstrate physics with limited consideration of EFD methodology and uncertainty analysis (UA). CFD is seldom included. A notable exception is the multi-media classroom developed at Worcester Polytechnic University for demonstrating relationship between analytical, numerical, and experimental methods[1] and the work of the authors[2], as described later. Advanced level courses are usually AFD with or without EFD and/or CFD assignment or EFD including methodology and in some cases UA. Recent developments have focused on development of CFD courses using specialty[3, 4] and commercial[5-7] software, which are sometimes combined with EFD[8, 9]. Computer assisted learning has also impacted fluid dynamics courses, such as using multi-media in teaching fluid mechanics[10], application of studio model[11], and development of computer-based textbook[12]. These studies have shown enhancement of the curriculum, increased learning efficiency and understanding, effectiveness of novel and *hands-on* learning methods, importance and need for educational interface design and pedagogy, and positive student response.

Authors[2] have contributed to integration of simulation technology into undergraduate engineering courses and laboratories through collaboration on the development of teaching modules (TM) for complementary CFD, EFD, and UA, including lectures on CFD, EFD, and UA methodology and procedures; CFD templates for academic use of commercial CFD; and exercise notes for use of CFD templates and complementary EFD and UA. The commercial CFD code is FLUENT. TMs based on *proof of concept* developed at The University of Iowa. Project supported by National Science Foundation 3-year award for faculty partners from colleges of engineering at large public (Iowa and Iowa State) and private (Cornell) and historically minority private (Howard) universities for collaboration on further development TMs, effective implementation, evaluation, dissemination, and pedagogy of simulation technology utilizing web-based techniques. The evaluation and research plan included collaboration among faculty and the University of Iowa, Center for Evaluation and Assessment. During the first year, pipe, nozzle, and airfoil TMs were successfully developed, implemented, and evaluated for an introductory fluid mechanics course at Iowa, for aerodynamics and gas-dynamics-laboratory courses at Iowa State, for a required fluid mechanics sequence at Cornell, and for an aerodynamics course at Howard. The evaluation results showed similar trends to other related studies and additionally used for formative evaluation purposes[13], as a guide for further developments CFD templates: educational interface for *hands-on* teaching CFD process, facilitating site testing same CFD template at different universities with different exercise notes, and broader dissemination. Here, *hands-on* defined as the use of EFD, CFD, and UA engineering tools in meaningful learning experience, which mirrors as much as possible *real-life* engineering practice.

The present paper describes the second-year project effort specifically on development of CFD educational interface for pipe, nozzle, and airfoil flows, including design for teaching CFD methodology and procedures, implementation based on site testing at partner universities, and evaluation. The evaluation based on field-testing investigates student learning and benefit from the revised efforts. Also discussed are further developments of CFD lecture, conclusions, and future work.

CFD Educational Interface

Whether or not specialty or commercial software used for teaching CFD, an educational interface to facilitate students' learning is required. Commercial software has the advantage that students may likely use same or similar software as professionals. Ideally, using educational interface at advanced level is essentially same as using commercial software itself.

Proof of concept (1999-2002) used FLUENT directly, which required lengthy detailed instructions (setting many parameters that were often unrelated to student application and difficult to explain or connect to a general CFD process) and did not facilitate options for modeling, numerical methods, and verification and validation studies.

Initiation present project coincided FLUENT release Flowlab version 1.0 (2002). The design of Flowlab was as a general-purpose CFD template, enabling students to solve predefined exercises. During the first year of the project, faculty partners collaborated with FLUENT Inc. on setting up templates for their respective courses and/or laboratories with agreed focus on introductory level and pipe and airfoil exercises. Collaboration faculty partners and FLUENT focused on modifications of Flowlab operations menu to more accurately reflect CFD process and capability and accuracy for specific student applications, including comparisons with AFD or EFD validation data. The evaluation confirmed that the implementation was worthwhile and promising, but at same time indicated direction for improvements. (1) Use of different specialized CFD templates for each exercise implied different CFD process for each application and did not facilitate site testing. (2) Exercises lacked options and depth. (3) Overly automated.

(4) Non-user-friendly interface was difficult to use. (5) Performance accuracy and flow visualization were substandard. Student anonymous responses suggested that students agree EFD, CFD, and UA labs were helpful to their learning fluid mechanics and important *tools* that they may need as professional engineers; however, they would like that learning experience to be more *hands-on* and tailored to their learning needs. Collaboration faculty partners and FLUENT during the second year of the project focused on development, implementation, and evaluation of the *hands-on* CFD educational interface.

Design Specifications The CFD educational interface designed to teach students CFD methodology (modeling and numerical methods) and procedures through interactive implementation for engineering applications. The CFD process is automated following a step-by-step approach, which seamlessly leads students through setup and solution of initial boundary value problem for application at hand. The CFD process mirrors actual engineering practice: geometry (solid and other fluid boundaries), physics (fluid properties, modeling, initial and boundary conditions), mesh, solve (numerical parameters), reports (monitor solution convergence), and post processing (flow visualization, analysis, verification, validation using imported EFD data and uncertainties). Predefined active options for students' exercises use a hierarchical system both for introductory and advanced levels and encourages individual investigation and learning. Ideally, transition for students would be easy from advanced level to using FLUENT or other industrial CFD code directly. A dynamically updated sketch window monitoring progress and enabling input parameter specifications is planned for future developments in conjunction with extensions for advanced level CFD templates, as will be discussed later. Generalizations of CFD templates for pipe, nozzle, and airfoil flows facilitate their use at different universities with different applications, conditions, and exercise notes using Flowlab version 1.1 (2003).

Pipe and Nozzle Flow Fig. 1 is a screen dump of the pipe flow template at a specific step of the CFD process and a flow chart for the pipe flow template showing all current active options available for students. Fewer active-options are available to students for the pipe flow than the airfoil flow template. The nozzle template is similar.

Airfoil Flow Fig. 2 is a flow chart for the airfoil flow CFD template showing all current active options available for students. More active-options are available to students for the airfoil flow than the pipe flow CFD template.

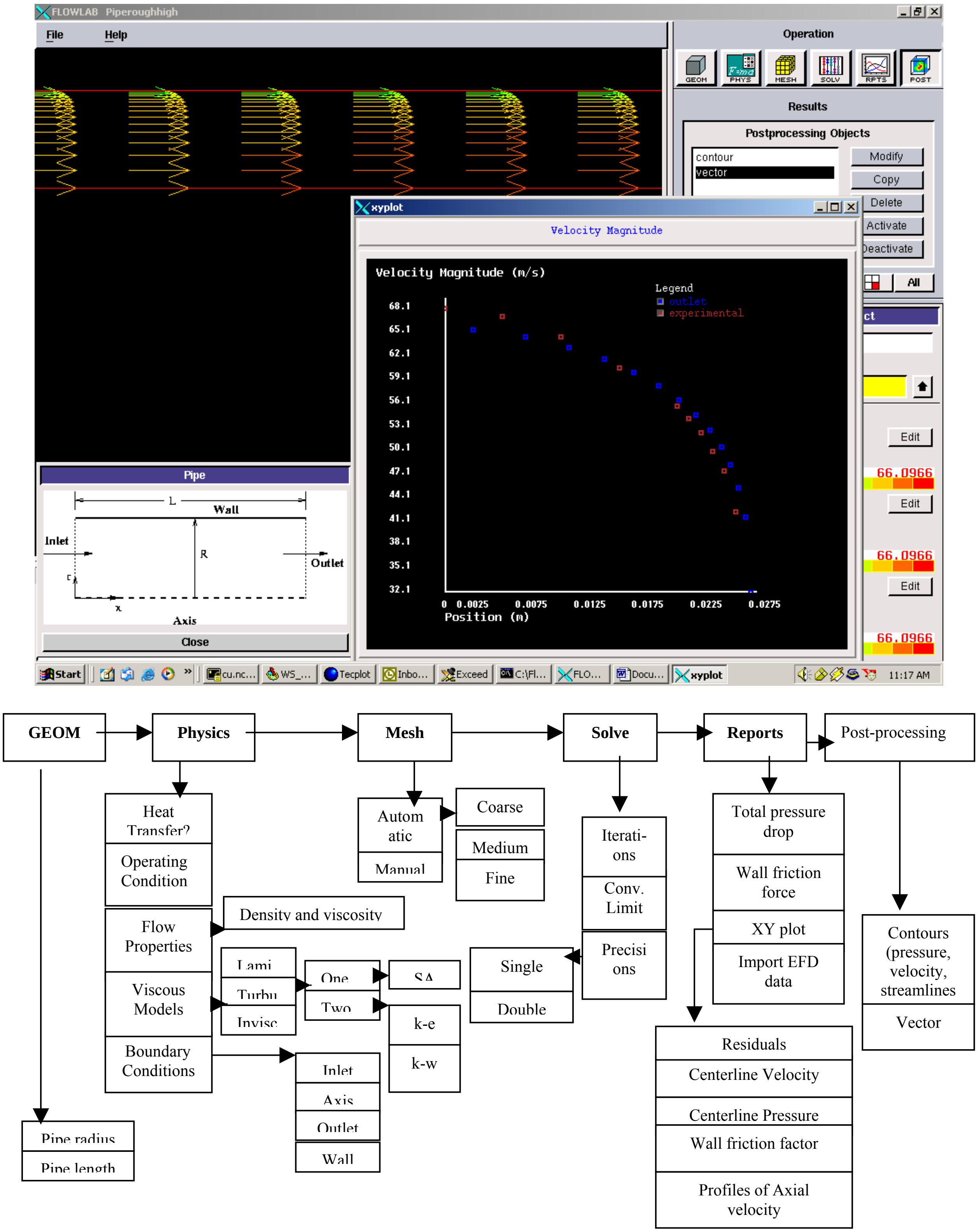

Fig. 1 Screen dump and flow chart for the pipe flow CFD template.

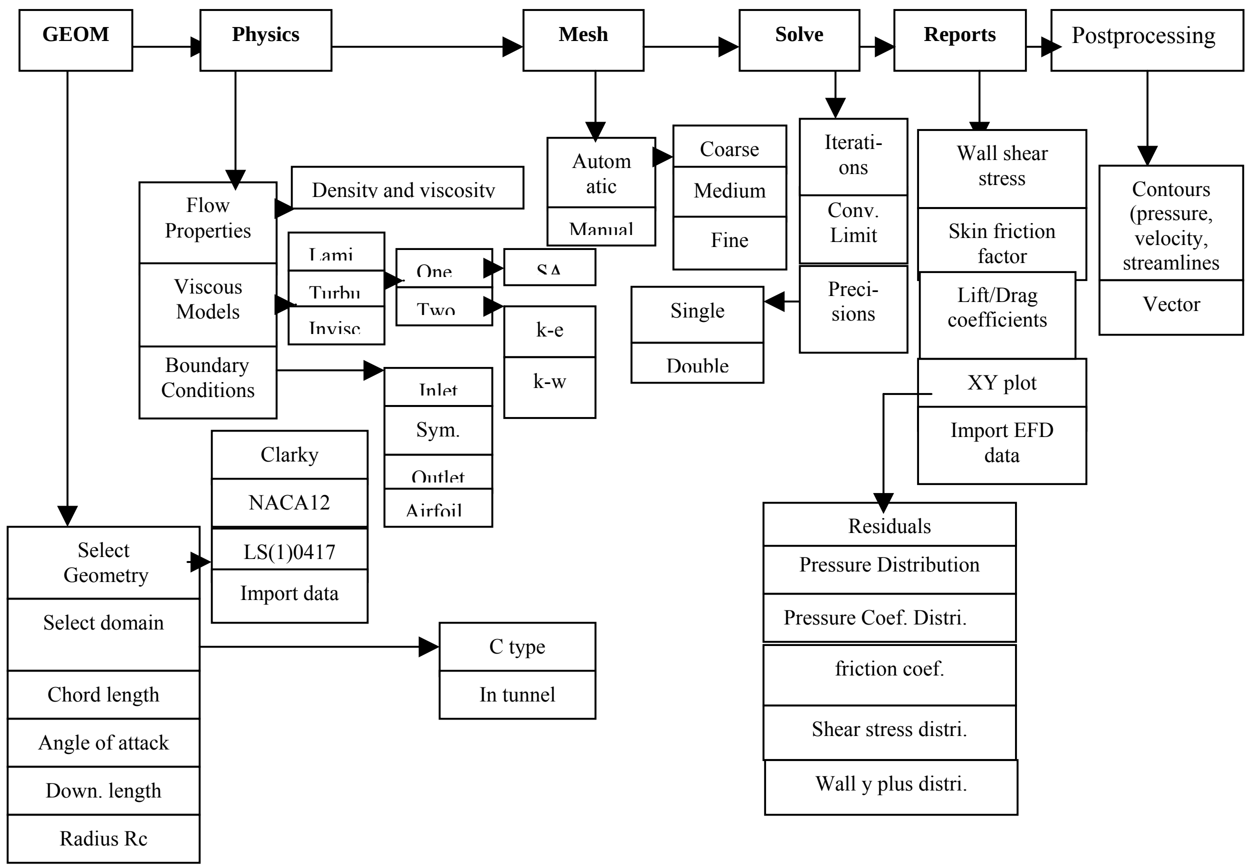

Fig. 2. Flow chart for the airfoil flow CFD template.

CFD Lecture Purpose of the CFD lecture is to prepare students for use of CFD educational interface using only one or two classroom 50-minute lectures. In general, faculty agreed on need, content (what, why, and where CFD; modeling; numerical methods; types of CFD codes; CFD process; example; and CFD educational interface and student applications), and desirability of collaboration on development of a common CFD lecture that could be site tested at different universities similarly as CFD educational interface. However, presently CFD lectures are not combined such that status described next in conjunction with site testing.

Site Testing

Site testing conducted for an introductory fluid mechanics course at Iowa, for aerodynamics and gas-dynamics-laboratory courses at Iowa State, for a required fluid mechanics sequence at Cornell, and for an aerodynamics course at Howard. Descriptions for Iowa, Iowa State, Cornell and Howard follow.

Iowa The introductory level fluid dynamics course at Iowa is a 4-semester hour junior level course required in Mechanical and Civil & Environmental Engineering and frequently elected by Biomedical Engineering students. Traditionally, course used 4-lectures per week for AFD with a few additional EFD labs for purpose of highlighting fundamental principles. Course restructured for 3-semester hour AFD (3 lectures per week) and 1-semester hour (1 laboratory meeting per week) complementary EFD, CFD, and UA laboratories. EFD laboratories upgraded for present purposes and to include UA and achieve benchmark quality data, including tabletop viscosity, pipe flow stand, and wind tunnel airfoil flow experiments. As discussed herein, complementary CFD laboratories were developed. The course was also reorganized for web based teaching and distribution of materials http://css.engineering.uiowa.edu/~fluids/.

Educational goals for lectures, problem solving, and the EFD, CFD, and UA labs were developed and used as guidelines for course and laboratory development, implementation, and evaluation. Table 1 lists the general goal for the complementary EFD, CFD, and UA labs as well as the detailed goals for the EFD, CFD, and UA labs. Although CFD labs at Iowa used with complementary EFD and UA labs, also designed for *stand-alone* use. At Iowa, some instructors choose to follow more traditional approach to teaching introductory fluid mechanics course using 4 lectures on AFD per week and placing less emphasis on EFD UA and complementary CFD, i.e., use only portion of lab materials presented herein.

Table 1. Goals for complementary EFD, CFD, and UA labs

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 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.Students will be able to apply CFD process through use of educational interface for commercial industrial software to analyze practical engineering problems. 3.Students will be able to conduct numerical uncertainty analysis through iterative and grid convergence studies. 4.Students will be able to validate their computational results with EFD data from their complementary experimental laboratories. 5.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.

A sequence of CFD, EFD, and UA labs developed to meet these goals. Labs intended for *hands-on* seamless teaching of CFD, EFD, and UA methodology and procedures as *tools* of engineering practice while at the same time relating results to fluid physics and classroom lectures. Table 2 provides an overview of the lab materials. During the first week of class, 1 classroom lecture is used to provide overview of AFD, EFD, and CFD as complementary *tools* of fluids engineering practice, which was followed throughout the semester by the AFD and problem solving lectures and EFD, CFD and UA labs. Students work in groups, but submit separate lab reports. EFD labs begin with lecture sequentially followed by viscosity, pipe flow, and airfoil flow experiments. Complementary CFD labs begin with lecture sequentially followed by pipe flow and airfoil flow simulations. Idea is for each lab to build on previous lab in sequence to achieve greater depth in each step of EFD or CFD process such that at advanced level students are nearly at level of engineering practice and additionally able to relate results to advanced fluid physics. Instructions provided for writing of lab reports, which constitute 25% of the final course grade. Instructions provided for each lab. Prelabs conducted for additional instruction. Students are also required to hand in answers to prelab questions to encourage their familiarity with lab materials before coming to the lab.

The class web site distributes the CFD lab materials. CFD lecture provides an overview of what, why, and where CFD is used, methodology (modeling and numerical methods), types of CFD codes, examples, and CFD educational interface. Lab report instructions guide students to write lab reports. Teaching assistants to grade the reports easily also use instructions. Different sections of lab report instructions are cross referenced to the Lab goals (Table 1), so the students' performances in the lab report can be used to provide evidence of students' skill and knowledge acquisition related to the lab goals. In Prelab 1, students were asked to learn how to run FlowLab following the CFD Process, be familiar with FlowLab interface, import and export data, and run simulation of laminar pipe flows with comparison to analytical solutions. In Lab 1, students conduct a more complicated case (turbulent pipe flow) and compare FlowLab predictions with their own EFD data obtained in EFD Lab 2. Students will simulate the inviscid flow around airfoil with different attack angles in PreLab 2 and conduct turbulent flow simulations on the same geometry in Lab 2 with validation by their own EFD data obtained in EFD Lab 3. Lab assignments use different options, such as investigations of effect of mesh refinement, effect of different turbulence models, and effect of different numerical parameters, etc. Students can choose the option that satisfies their interests the most. A companion paper at this conference describes EFD lab materials[14].

Table 2: TM used for introductory fluid mechanics course at Iowa (EFD/CFD lab materials).

Lecture	**Other Docs**	**Lab 1: Viscosity**	**Lab 2: Pipe Flow**	**Lab 3: Airfoil**
EFD lecture	EFD UA Report Lab Report Instructions	Pre lab1 questions Lab1 lecture EFD 1	Pre lab2 Questions Lab2 lecture EFD 2 Lab2_UA:	LAB3 lecture EFD 3 Benchmark Data Data Reduction Sheet

		Lab1_UA Instructions_UA	Smooth Rough Instructions_UA	Instructions_UA Combined EFD3/CFD2 report instructions
CFD Lecture	CFD lab report instructions	None	CFD Prelab1 CFD Prelab1 lecture CFD Prelab 1 questions CFD Lab 1	CFD PreLab2 CFD PreLab2 Lecture CFD Prelab2 questions CFD Lab2

Self-Evaluation As part of the overall evaluation process, a self-evaluation was performed based on analysis of the data from students' performance and comments from their EFD reports, college of engineering EASY survey, and Course Outcomes Assessments Administered by Center for Evaluation and Assessment data were analyzed. Most students' performance was very good, cooperative, and eager to learn. Students appreciated the *hands-on* learning process by using a step-by-step method through the educational interface, which enhanced their understanding of the CFD process to analyze and solve practical fluids engineering problems. The analysis also suggested several ways to improve implementation. (1) FlowLab: develop user-friendlier FlowLab interface and increase the depth of CFD templates. (2) Lab reports: combine the CFD and EFD lab reports and TA's lab reports grading is too liberal and does not break the grades to different categories as required by the lab report instructions. (3) Lab design: develop interactive and effective use of PreLab and Lab time. (4) Hands-on: provide more access to FlowLab and one-person one-computer to provide more *hands-on* experiences as required by students. Improvements planned for implementation for Fall 2004 for both introductory and advanced level CFD templates. The introductory level templates used for the current fluid class and the advanced level templates used for teaching an intermediate fluid class.

Iowa State Implementations conducted for aerodynamic sequence of courses and the gas-dynamic-laboratory course.

Aerodynamics I Lab The required aerodynamic sequence of courses at Iowa state are structured as incompressible potential flow (AERE 243. Aerodynamics I), compressible flow (AERE 311. Gas Dynamics) and viscous flow (AERE 343. Aerodynamics II).

Each of these courses is also strongly coupled with a lab course (AERE 243L. Aerodynamics I Lab, AERE 311L. Gas Dynamics Lab and AERE 343L. Aerodynamics II Lab respectively). The classes in general address AFD while the labs are used as EFD test-beds for certain concepts introduced in the class. CFD through the Fluent software was introduced in the first two labs Aerodynamics I Lab and Gas Dynamics Lab as part of the NSF project. In this paper we discuss the introduction of CFD (through the Fluent software) in Aerodynamics I Lab and Gas Dynamics Lab, and its impact on student learning in these courses.

Aerodynamics I Lab is a half a semester course and specifically discusses the following four concepts:

Concept 1. Streamlines, streak lines and path lines (AFD) and their connection to Flow visualization. Smoke tunnel is used in the EFD lab to visualize flow over two-dimensional and three-dimensional objects in the lab. Flowlab is introduced in this lab as a demonstration by the instructor. Snapshots from EFD and CFD are prosecuted below.

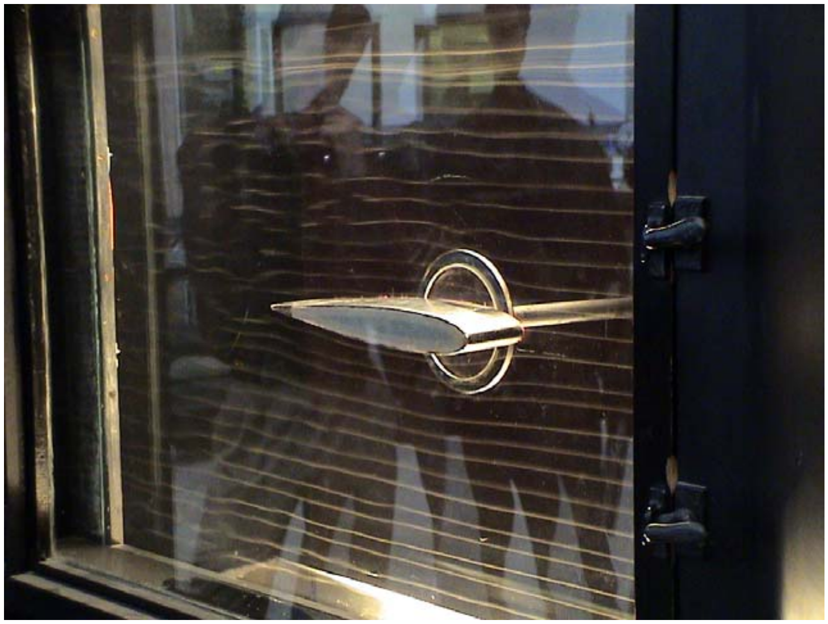

Fig. 3. Streamlines (experiment)

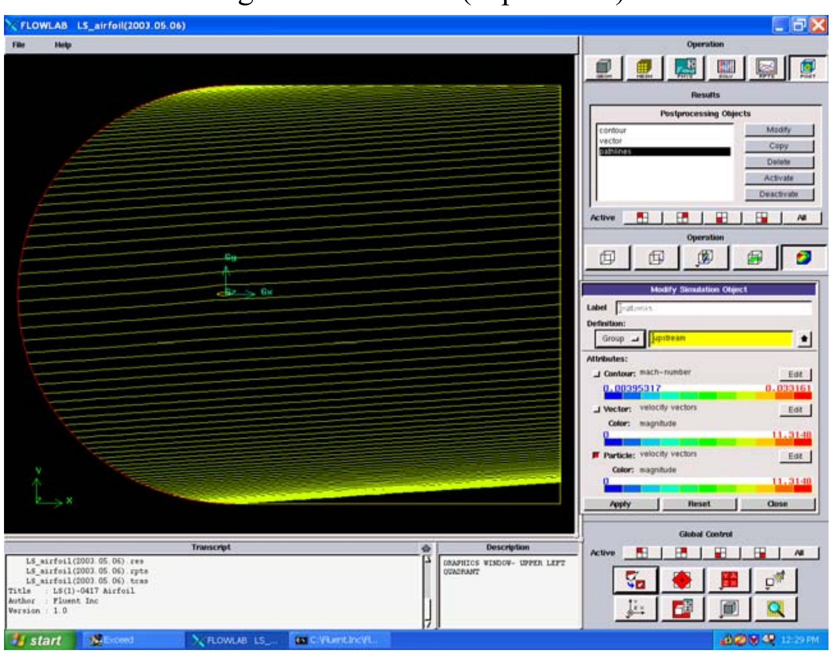

Fig. 4. Streamlines (FlowLab)

Concept 2. As an application of the Bernoulli's equation taught in the theory class a closed circuit wind tunnel is calibrated in the EFD lab.

Concept 3. Flow over a circular cylinder is introduced from the point of potential flow in the theory class. In the Lab course the pressure distribution over the 2-D cylinder is observed and contrasted with the potential flow solution. CFD use is required in this lab. The students are required to conduct the same experiments numerically using Flowlab and compare AFD, EFD and CFD results in the report they write. Examples from students work are presented in the following illustrations.

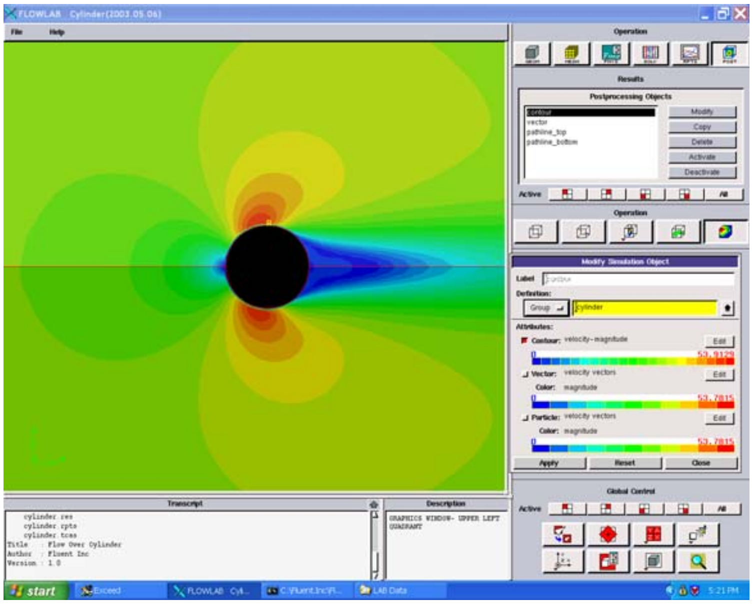

Fig. 5. Numerical results for the velocity magnitude distribution over a circular cylinder using FlowLab (Vh=35.8 m/s, Re=1.89E+05)

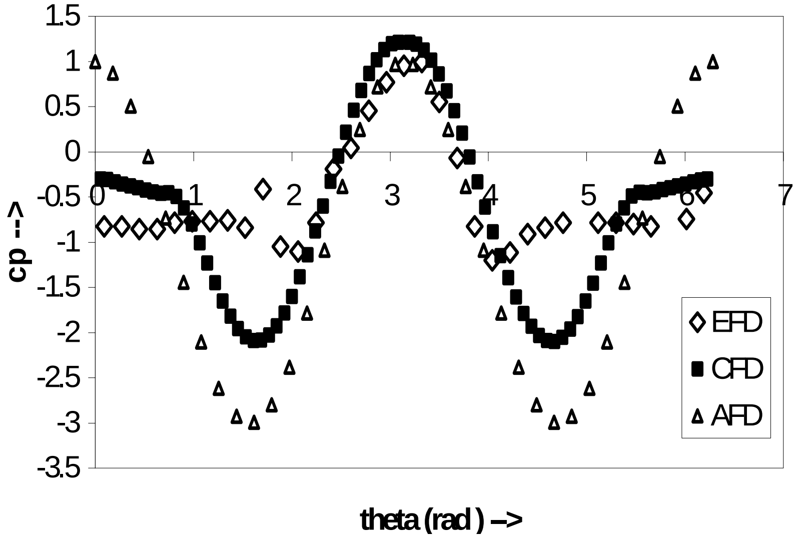

Fig. 6. Cp distributions over a circular cylinder

Aerodynamics I and the associated lab Aerodynamics I Lab are introductory courses and are sophomore level classes. CFD is introduced as a procedure for solving the partial differential equations that describe the flow. Students are encouraged at this level to become expert users of CFD through Flowlab, however, they are not required to know the details of the CFD theory.

Concept 4. The final lab involves the aerodynamic characteristics of an airfoil (Cl vs. α, Cd vs. α and Cm vs. α) using pressure measurement. Flowlab is used to conduct the same experiments numerically and pressure measurement comparison with EFD is presented in the following illustrations.

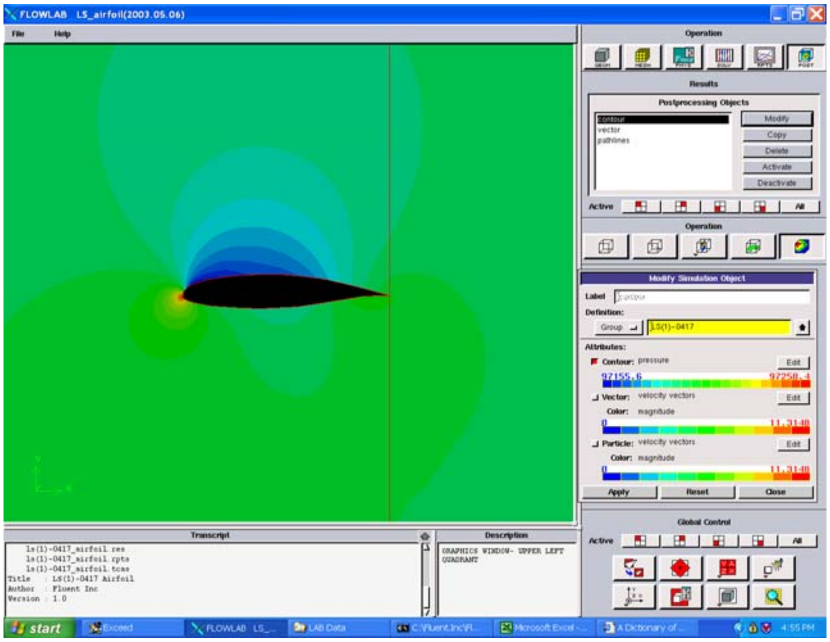

Fig. 7. Numerical results for the pressure distributions over LS(1)-0417 airfoil using the Flowlab (angle of attack=4 degree, Mh=0.025, Re=2.0E+05)

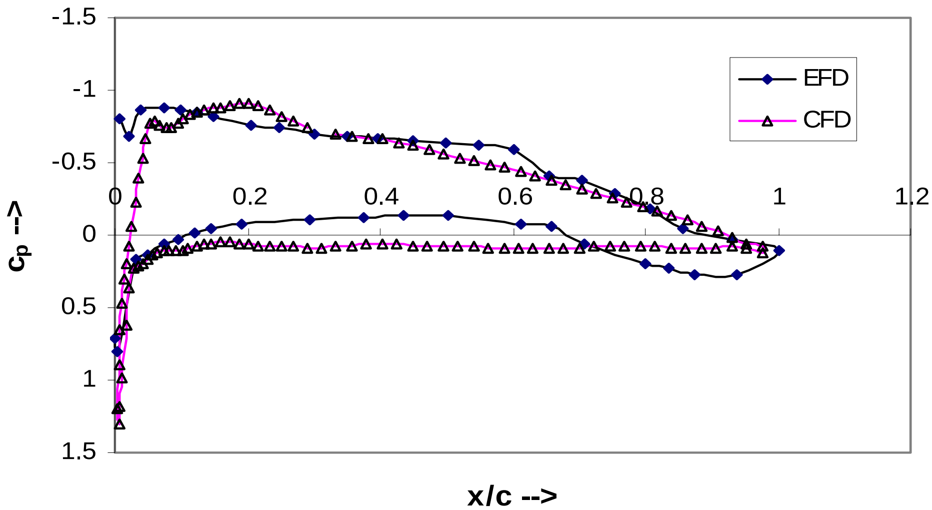

Fig. 8. Cp distributions over LS(1)-0417 airfoil

Table 3 Key results from AERO E. 243L survey								
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 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

The gas-dynamics-laboratory course The gas-dynamics-laboratory course taught at Iowa State University is a junior level course. This 0.5 credit hour course complements a 3-credit hour lecture course. Being taught in the second half of the semester, the laboratory course reviews the theory, and introduces experimental procedure and CFD analysis using Flowlab.

The first experiment taught in the course examines the time evolution of pressure and temperature in the blowdown of a high pressure tank. The second experiment considers wall pressure measurements for different shock positions within a nozzle which is connected to the tank. As air is blown through the nozzle, there is gradual change in the observed flow patterns, from expansion fans through oblique shocks and normal shocks within the nozzle. Students examine the 1st, 2nd and 3rd criticals for the nozzle using a combination of experiment, theory and CFD. The 1st critical refers to the case when the throat Mach number is 1, 2nd critical for a standing shock at the nozzle exit and 3rd critical for a smooth flow devoid of shocks and expansion fans.

Bearing in mind that the class met once every week for seven weeks of the semester, the first two weeks of the class were used to acclimatize students to the Schlieren method of flow visualization as well as to present an overview of the one-dimensional nozzle theory. In the third week, the first blowdown experiment was performed in groups of 4 students. An introduction to

CFD using Flowlab was given in the third week. The lecture consisted of an overview of CFD methods and Flowlab, accompanied by a tutorial section for each segment – such as defining physics, creating mesh and solving for the result. The objective of the CFD lecture was to emphasize the actual CFD decision making process when using Flowlab.

A second CFD lecture was given in the fourth week, along with CFD practice sessions. The second CFD lecture covered additional physics and mathematics, such as the need for grid stretching and the properties of shock boundary-layer interactions. The second experiment as well as CFD exercises were performed in the fifth and sixth weeks. The second experiment involved measurement of wall pressure for six cases: under-expanded flow, 3rd critical, over-expanded flow with oblique shock, 2nd critical, shock between throat and exit of the nozzle, and 1st critical. The second CFD exercise consisted of two parts. In the first part, the students reproduced one of the cases from the experiment. In the second part, the students used a tank pressure value between 1st and 2nd critical to create and visualize a λ-shock.

The CFD solutions from Flowlab were found using a nozzle template developed by Fluent. Close interaction between Iowa State and Fluent resulted in a template which provided acceptable comparison with experiment as well as reasonable run times.

The Flowlab template for the nozzle was designed to use three types of meshes with varying degrees of mesh density: coarse, medium, and fine. All of these meshes take into account the presence of the boundary layer. The primary control parameters for the simulation are inlet total pressure and the flow model (e.g. inviscid, laminar or turbulent). Two flow geometries were used in our class (axisymmetric and 2D). A complete 3D calculation for the rectangular cross-section nozzle which was actually used in the experiment would take more time than we deemed to be acceptable.

The CFD exercises for Flowlab were tested using a computer with 512 MB RAM and an Intel Pentium 4 1.8 GHz processor. Students performed the Flowlab exercises in a departmental computer lab with computers which had two 866 MHz Pentium III processors and 512 MB RAM.

As seen in Table 4, it was observed that most of the cases had run times of 10-20 minutes when using the medium mesh configuration and an inviscid model. Fine mesh cases took 1.5 to 2 times longer than the medium mesh configurations. The run times for 2D and axisymmetric cases were similar. However, some cases involving inviscid flow took a long time for convergence. For example, when a plenum was added to the nozzle exit between 1st and 2nd criticals, and inlet total pressure was 170000 Pa, the time taken for convergence was more than the case without the plenum and same inlet pressure. This time was also more than the time taken for a case with plenum and inlet total pressure close to 2nd critical. It should also be noted that the λ-shock case exhibited strong oscillatory behavior in convergence. In addition, the λ-shock from Flowlab was seen to be larger than the shock observed in the experiment.

Table 4. Flowlab run times with medium mesh				
Inlet pressure	Flow model	Run time (in minutes)	Number of iterations (approx)	Convergence Limit
114845 Pa – (1st critical – From expt. = 108,220 Pa)	Inviscid	5	230	10^{-3}
250000 Pa+ – (2nd critical – From expt. = 253,010 Pa)	Inviscid	15	1100	$2x10^{-3}$ *
450000 Pa+ – (3rd critical – From expt. = 446,063 Pa)	Inviscid	9	315	10^{-3}
163000 Pa – λ-shock	Turbulent (k-ε)	23	1550	10^{-3}

* - iteration usually required interruption, since the residual for continuity oscillated around this number.
\+ - based on visual examination

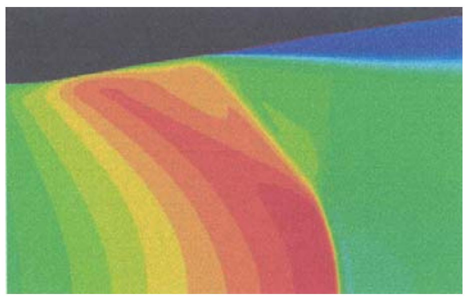
Fig. 9. Typical Mach number contour for a λ-shock using Flowlab.

A Mach number contour from a student's report is shown in Fig. 9. In this figure, the Spalart-Allmaras model was used as the turbulence model. An inlet total pressure of 165,000 Pa and an outlet pressure of 1 atm were used, which produced a shock in the diverging section of the nozzle.

A course survey was conducted and administered by the University of Iowa. Some of the key results are presented below. In this table, n is the number of students, and AFD and EFD refer to analytical and experimental fluid dynamics, respectively.

Table 4.1 Scales used in survey						
Strongly Agree	Moderately Agree	Mildly Agree	Mildly Disagree	Moderately Disagree	Strongly Disagree	No Opinion
SA	A	A	d	D	SD	nop

Table 4.2 Key results from survey

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

In the survey, it was found that most of the responses were around ‘A’ and ‘a’. The questions for the assessment of work done for the lab reports received ‘SA’ and ‘A’ responses, which meant that most students had participated in preparing the lab reports. Responses to CFD related questions, which are tabulated above, indicate that students indeed benefited from the usage of Flowlab.

Though most students assessed the volume of material covered to be correct, there were a few students who observed 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.

Cornell The pipe flow template was used in a required senior-level fluid mechanics and heat transfer lab course. The class had 110 students with 2 professors and 6 teaching assistants providing instruction. The lab was taught in small groups of 6-8 students. The lab experiment involved turbulent flow of air through a smooth-walled copper pipe duct consisting of three sections. The first section was unheated and generated a hydrodynamically fully-developed turbulent velocity profile, the middle section was heated providing energy input to the air, and the final section was insulated providing an adiabatic mixing length to allow a single or bulk reading of the final air temperature. The apparatus was equipped with instrumentation for measuring (1) air mass flow rate, (2) pressure drop over a given length, (3) temperature distribution along the duct wall and temperature rise of the air, (4) temperature profile at the exit of the duct, and (5) energy input to the heating ribbon. In previous years, this lab involved operation at one heated condition (corresponding to a single Reynolds number and Nusselt number) and several unheated conditions. In order to accommodate complementary numerical simulations using FlowLab, the lab was modified to include operation at one heated condition only with operation at the unheated conditions being dropped.

In the first week of the lab for each student group, the instructor introduced the experimental set-up and data acquisition as well as the pipe flow template. The hands-on template introduction involved each student following directions from the instructor for simulating the heated pipe flow using sample input data. This was done in a computer lab adjacent to the experimental apparatus. In the second week, data processing was discussed in a recitation session. The lab report was due a week after that. Students were provided with a handout that discussed (1) the basic strategy of CFD, (2) the CFD solution process, (3) the details of stepping through this process in the pipe flow template, (4) background on turbulence modeling, and (5) operating details of running FlowLab, such as controlling the graphical display and exporting files into Excel, and using the computer lab. This handout will be made available on the FlowLab website as an example for interested instructors at other universities.

In their reports, students were required to compare the friction factor and Nusselt number obtained from their experiment with corresponding values from their FlowLab simulation and correlations in the literature. A typical comparison of the results for a Reynolds number (based on pipe diameter) of 100,820 is shown in Table 5. The simulation results compare reasonably well with those from experiment, with the difference in friction factor and Nusselt number being 7% and 4%, respectively.

Table 5: Typical results for the pipe flow lab at Cornell university.

	Experiment	**Simulation**	**Correlation**
Friction factor	0.0180±0.003	0.0168	0.0177
Nusselt no.	185	192	183

The pipe flow template enabled students to visualize velocity vectors and the temperature field which helped them gain a better physical understanding of the experimental system than is possible from a few point measurements. This was noted by a majority of students in their course evaluation. The template helped them appreciate that numerical modeling involves approximations and tradeoffs. The simulations were used to confirm some of the assumptions made in data reduction for the experiment, for instance, that the adiabatic mixing region is long enough for the temperature to be uniform at its exit. The template results provided confirmation of the experimental and correlation results, and showed how these approaches can complement each other.

We worked closely with personnel at Fluent Inc. to insure that the pipe flow template met the requirements at Cornell. For example, a feature enabling specification of constant heating along a specified subsection of the pipe was added at our request. There were some early problems with the template that resulted in program crashes and poor agreement with experiment. Fluent Inc. personnel paid a visit to Cornell to discuss the problems and responded in a timely fashion to fix them before student use of FlowLab. Our experience was that small groups were well-suited to introducing students to CFD basics through FlowLab. The FlowLab experience resulted in many students showing an enthusiasm for learning more about CFD.

Howard The airfoil and pipe flow templates were used in a required, junior-level fluids mechanics course (MEEG 307). There were 15 students in the class and the students were divided into groups of three. The simulation component of the course began with an introduction to CFD and error analysis. The students then used the templates and FlowLab in open-ended homework problems and as a design tool for laboratory experiments for the following semester. Unlike at the other partner institutions, the fluids/thermal laboratory component at Howard University occurs in the second semester. The formal assessment will be performed in the spring semester when we incorporate the EFD component of the project. However, informally we received a positive response from students and the suggestion that the simulation be introduced earlier in the semester. The course may be redesigned for the Fall 2004 semester if the responses are similar for the companion course.

Evaluation

The evaluation design treats each of the four sites as separate case studies applying instructional techniques and software in the context of different curricula at the different sites[15]. Course goals at each site are related to the ABET standards, but are expressed in terms of the general engineering course goals and objectives at each site.

The guiding evaluation questions addressed by this design are the same at each site:

- Were student learning needs met and did the students benefit from the implementation of the CFD software and instructional interfaces? If so, in what ways did they benefit? If not, why not?
- In what ways can the efficiency or the effectiveness of the CFD products and implementation be improved?
- What are especially important strengths of the current implementations that need to be maintained in the next year or for future implementations at other schools and colleges of engineering.

Methodology The methodology used in this evaluation design envisioned three primary sources of information:

1. Faculty and Teaching Assistant judgments of the quality of lab reports and/or of exam results.
2. Student responses to independent, anonymous survey items asking them to judge their own learning from specific instructional components in retrospective fashion, a method with investigated and documented validity for low stakes judgments[16].
3. Student responses to independent, anonymous survey items asking them to provide evaluations of all the separate implementation components and to comment on how to improve the efficiency and effectiveness of the implementation, especially *hands-on* components

The survey items were developed separately for each university site and collaboratively with faculty from each site. Students responded to the survey items during the last week of class with anonymity and without the instructor present. Site IV will participate in future data collection. Surveys included some shared items, but focused primarily on the tailored instructional goals at each site. Complete versions of the surveys as administered are available as PDF files at the following Web site: http://www.iihr.uiowa.edu/~istue/. Open-ended survey items requested respondent comments. Students were also asked to respond to direct statements indicating their degree of agreement or disagreement (e.g., "This course increased my interest in fluid mechanics" or "As a result of my learning in the CFD labs, I am able to present results from CFD simulations in written and graphical form). Respondents were asked to agree or disagree on a six point Likert type scale ranging from "strongly agree" (scored as 6) to "strongly disagree" (scored as 1) scale. Respondents with insufficient information or who otherwise did not want to respond could choose a "no opinion" response.

Results for the Site I implementation Student lab reports At Site I, lab reports were originally scored for general quality and learning outcomes as part of the grading process. After the end of the grading process, a post-doctoral associate and the PI analyzed the lab reports to document the extent to which student lab reports provided evidence of students' skill and knowledge acquisition related to the CFD implementation goals. The evaluation team is currently reviewing these procedures and analyses to investigate their reliability and generalizability (validity).

Table 6 presents the percentage of students at the Site I implementation whose lab reports indicated that specific instructional goals had been achieved.

Table 6: Percentages of lab reports providing evidence of specific goal attainment, as judged by the course instructor and teaching assistants

Goals	Student Performance		Reports Sections
	Lab1	**Lab2**	
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.	96%	96.5%	Total
2. Students will be able to apply CFD process through use of educational interface for commercial industrial software to analyze practical engineering problems.	100%		3
3. Students will be able to conduct numerical uncertainty analysis through iterative and grid convergence studies.	N/A		4
4. Students will be able to validate their computational results with EFD data from their complementary experimental laboratories.	100%		3,4
5. 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.	91%		4,5

Site I Survey Responses. For purposes of this report, survey items were categorized into clusters addressing the following topics:

- General Learning Needs Met by the Course (23 items, for example: "My learning needs were well met in this course", "The information in this course was presented effectively"
- Hands-on aspects of the CFD Component (2 items: "The hands on aspects of the Computational Fluid Dynamics Lab helped me learn valuable skills and knowledge", The hands-on aspects of the Computational Fluid Dynamics Lab worked well for me"
- Skills and Knowledge Gained Using the CFD Component (10 items: "As a result of my learning in the CFD Lab, I am able to use Flowlab for solving laminar and turbulent pipe flow and inviscid and viscous airfoil flow", "As a result of my learning in the CFD Lab, I am able to evaluate grid convergence through analysis of solutions on coarse, medium, and fine grids.

Table 7 lists the items included in each cluster score. All cluster scores were investigated to determine their reliability[17]. Table 7 presents the internal consistency reliability estimates of the three cluster scores as well as their simple Pearson product moment correlations with each other.

Table 7. Cluster score reliability estimates and product moment intercorrelations

	Learning Needs Overall	Hands-On CFD	Skills, Knowledge Gained CFD
Learning Needs Overall	.94[a] (54)		
Hands-On CFD	.58 (54)	.92[a] (54)	
Skills, knowledge Gained CFD	.64 (54)	.74 (54)	.95[a] (55)

Note. Numbers in parentheses indicate the number of cases from a total of 62 students who provided some survey information. [a] Cronbach's Alpha reliability coefficients

As can be seen in Table 7, all cluster scores showed high reliability estimates and moderate correlations with each other, suggesting that they provided good measures of the named constructs, and that respondents were able to differentiate the three constructs from one another. For example, the R^2 for the simple correlation of the cluster score "Hands-On Aspects of CFD" with the cluster score "Learning Needs Met Overall" (R^2 = .64 squared = .40) suggested that only about 40% of the variance in students' responses to the items constituting one of these cluster scores can be explained by students' responses to the other cluster score.

Of greater interest for the evaluation of the CFD implementation are the averages and distributions of students responses to the items clustered into these constructs. In general, the more strongly the students agreed with these items (or disagreed with the reverse, negatively stated items) the more support they were expressing for the extent to which their overall learning needs were met, for the quality of the hands-on components, or for the knowledge and skills gained from the CFD implementation.

Table 8 presents the means and standard deviations for each of these three cluster scores. Cluster scale scores are the sum of all scale item responses divided by the number of items in that cluster in order to give the cluster scores for each individual the same range and anchors (6=Strongly Agree, 1=Strongly Disagree).

Table 8. Cluster score means and standard deviations

Scale	*N* Cases	*N* Items	Mean	SD	Minimum	Maximum
Learning Needs Overall	55	24	4.56	0.65	2.81	5.63
Hands-on CFD	55	2	3.44	1.36	1.00	6.00
Knowledge, Skills CFD	55	11	4.40	0.93	2.00	6.00

As can be seen in Table 8, respondents on average "mildly to moderately" agreed that their overall learning needs were met (M=4.56 out of a possible 6.0, SD=.65) and "mildly to moderately" agreed that their knowledge and skills improved as a result of the CFD lab (M=4.40, SD=.93). However, students on average were not in agreement with statements about the quality of the *hands-on* experience in the CFD lab either helped them learn valuable skills and knowledge or worked well for them (M=3.44, between "mildly agree and mildly disagree", SD=1.36) . The variability of cluster scores was great: individual student cluster score responses ranged from strongly disagree to strongly agree. Thus on all cluster scores, some students appeared to be well-satisfied with these efforts while others appeared to be in strong disagreement that these CFD implementation efforts were effective for them.

Students were also given the opportunity to respond to open ended survey items elaborating on their evaluations of the CFD labs and the hands-on components of the labs. In response to the question: "In your own words, what are the best things about learning with the CFD lab?", 59 of 62 students provided comments. Two raters independently categorized all comments into one or more of 7 categories (overall rater agreement, Kappa = .76), listed below.

<u>Useful, new understanding/knowledge</u>: 10 responses. For example, respondents mentioned the speed of getting results helped learning, that they appreciated learning the new software, and that they were acquiring "knowledge of a program that is being used in many businesses…will be a good tool in the future."

<u>Quality of the hands-on aspects</u>: 7 responses. For example, students mentioned that "the hands on aspect is best"…getting to see graphical data, using the software to understand what is going on in a flow, seeing what you learned in the lecture, and being able "to use technology instead of raw equations to obtain answerable solutions."

<u>Quality of the software capabilities</u>: 13 comments. Students mentioned the visual operating format that "combines multiple data processing programs", the graphs, ability to change the angel of attack for airfoil experiments, ability to impact any parameter and see the output instantly, ability to pick questions, experiments and factors of individual interest, and ease of set-up and error correction.

<u>Value of visualization of results</u>: 14 comments. Students commented on the power of the graphical presentations to make the output interesting and meaningful. Several indicated this was the best thing about the CFD. Several thought the post processing visualization was useful in understanding what was going on.

<u>Value of instruction or teaching</u>, 7 responses. Students commented on TAs being helpful and on the usefulness of the step-by-step approaches.

<u>Miscellaneous negative comments</u>: 7 comments. Even though this question asked for benefits, seven respondents indicated that they did not benefit, found the software confusing and unhelpful, or were not able to learn from the TAs.

In response to the question: "What needs to be improved in the CFD lab to maximize its value to you?", 59 students out of 62 provided comments. Two raters independently categorized all comments into one or more of three categories below (overall rater agreement, Kappa = 0.72).

Increased access/individual use: 10 comments. Students wanted more computers so that individual access to the keyboard for everyone would be possible.

Technical aspects/software: 7 comments. Students complained about the physical facilities, the colors on the screen, computers locking up, and especially unfriendly user interfaces.

Instruction/organization: 30 comments. Students wanted better organization, clearer instructions and guides, better understanding of what specific things mean, better collaboration between the experimental flow lab and the CFD, smaller groups, more time to learn and more long-term integrated projects, better instructions, and so forth.

Site II Results At Site II, no lab reports were analyzed. However, extensive open ended and Likert type items were administered to students in the fluid dynamics course. For purposes of this report, the Likert type survey items were categorized into clusters addressing the following topics three topics.

- General Learning Needs Met by the Course: (23 items, for example: "My learning needs were well met in this course", "The information in this course was presented effectively")
- Knowledge and Skills acquired through the CFD Component: (12 items: "CFD taught me things that I could not learn through EFD or AFD alone", "I can relate CFD results to fluid physics presented in the lecture course").
- Quality of the Hands-On Components: (2 items: "The hands-on aspect of the CFD lab worked well for me", "The hands-on aspects of the CFD Lab helped me learn valuable skills and knowledge").

Table 9 lists the items included in each cluster. All cluster scores were investigated to determine their reliability[17]. Table 9 presents the internal consistency reliability estimates of the three cluster scores as well as their simple Pearson product moment correlations with each other.

Table 9. Cluster score reliability estimates and product moment intercorrelations for Iowa state university.

	General Learning Needs	Hands-On CFD	CFD Knowledge & Skills
General Learning Needs	.95[a] (28)		
Hands-On CFD	.53 (28)	.89[a] (28)	
CFD Knowledge & Skills	.62 (28)	.67 (28)	.95[a] (28)

Note. Numbers in parentheses indicate the number of cases from a total of 28 students who provided some survey information. [a] Cronbach's Alpha reliability coefficients

Similar to the data summaries from Site I, these correlations and internal consistency estimates indicate that the cluster scores are measuring somewhat different constructs and display a high level of internal consistency reliability.

Also at Site II, of greater interest are the measures of central tendency and variability for the cluster scores. Table 10 presents the means and SDs for these three cluster scores.

In general, the more strongly the students agreed with these items (or disagreed with the reverse, negatively stated items) the more support they were expressing for the extent to which their overall learning needs were met, for the quality of the hands-on components, or for the knowledge and skills gained from the CFD implementation.

As before, cluster scale scores are the sum of all scale item responses divided by the number of items in that cluster (in order to give the cluster scores for each individual the same range and anchors, 6=Strongly Agree, 1=Strongly Disagree).

Table 10. Cluster score means and standard deviations

Scale	*N* Cases	*N* Items	Mean	SD	Minimum	Maximum
General Learning Needs	29	12	4.20	0.85	2.12	5.65
CFD Knowledge & Skills	29	12	4.62	1.07	1.00	5.63
Hands-On CFD	29	2	4.14	1.06	1.00	5.50

As can be seen in Table 10, respondents on average "mildly to moderately" agreed that their overall learning needs were met (M=4.20 out of a possible 6.0, SD=.85) and "mildly to moderately" agreed that their knowledge and skills improved as a result of the CFD lab (M=4.62, SD=.1.07). In addition, students on average mildly agree that the quality of the *hands-on* experience in the CFD lab either helped them learn valuable skills and knowledge or worked well for them (M=4.14, SD=1.06). It's important to note that the variability in all of these cluster scores was great, and that individual student cluster score responses ranged from strongly disagree to strongly agree. Thus on all cluster scores, some students appeared to be well-satisfied with these efforts while others appeared to be in strong disagreement that these CFD implementation efforts were effective for them.

Students were also given the opportunity to respond to open ended survey items elaborating on their evaluations of the CFD labs. In response to the question: "In your own words, what about the CFD component worked especially well for you or was especially beneficial to you?", 25 of 29 students provided comments. Two raters independently categorized all comments into one or more of four categories (overall rater agreement, Kappa = 0.72):

<u>Quality of the Hands-On Component</u>: 6 comments. Students commented that they liked the hands-on nature of the CFD lab and that they liked practicing it.

Value of Visualization of Results: 9 comments. Students commented that it was "nice to see the physical data showing shocks" or that it was valuable to see "the flow move as a result of changes in inlet and outlet pressure," and/or that obtaining and seeing the many different contours was valuable.

Ease of Use: 5 comments. Five respondents commented that the CFD was easy to use.

Negative Comments: 3 comments. Three respondents provided negative comments even though the survey question asked for the useful and beneficial aspects. One said that there was not enough time spent on setting it up; another said that it was a waste of time when it "blew up." The third said that the best thing about it was "when it was over".

Students also responded to the question: "In your own words, what about the CFD component should be changed the next time it is taught? What needs to be improved?" 21 of 29 student respondents provided comments, which two raters then categorized into one of two categories (Kappa = 0.72).

Changes to technical aspects: 8 comments. Students said that Flowlab bugs needed to be fixed, that the software needed to be fixed, that it needed to be easier to print, and that occasionally Flowlab gives results that were not anywhere close to those obtained from real experiments.

Changes to instruction and teaching: 13 comments. Respondents listed a number of areas that needed improvement, including specific topics, for example, more clearly explaining the viscid modeling and designing manual meshes. More general comments included "…more time spent explaining Flowlab and setting it up", or requesting more instruction, or asking for less lecturing or more lecturing. Two comments requested more hands-on time. One student thought that Flowlab was more trouble than it was worth and not very dependable, asking instead that "Fluent should be taught directly".

Results from the Site III implementation The survey administered at Site III was shorter than the other surveys and only addressed the CFD component. Nine Likert type scale items, scored as described previously, addressed the knowledge and skills acquired. These items all began with the stem, "As a result of my learning in the CFD Labs, I am able to" and continued with such statements as "present results from CFD simulations in written and graphical form," or " run Flowlab and implement CFD process for laminar and turbulent flow." The average over all items for 77 of 80 responding students was 4.16 (SD = 1.15 students), indicating that students, on average, "mildly agreed" with these statements. Strongest agreement (M=4.63, SD = 1.16) was for the item, "…I am able to appreciate that simulation involves approximations and tradeoffs". Least agreement, (M=3.68, SD = 1.20, between "mildly agree" and "mildly disagree") was for the item, "…I am able to evaluate iterative convergence through setting iterative convergence criteria and analysis of solutions residuals." As with the other institutions, the most striking aspect of the responses is the variability, ranging from "Strongly Disagree" to "Strongly Agree" on all items.

Students were also given the opportunity to respond to open ended survey items elaborating on their evaluations of the CFD labs. In response to the question: "In your own words, what are the best things about learning in the CFD lab, 58 of 81 students commented. Two raters independently categorized all comments into one or more of five categories (overall rater agreement, Kappa = 0.72):

Increases in understanding and knowledge: 15 comments. Students' responses included the value of learning the software and the interface, learning the theory modeled by the software, comparing the CFD to the experimental results, learning more about simulation, learning about flow and how to plot out results, and learning about the trade-offs and limitations.

Quality of the hands-on aspects: 6 comments. Respondents commented on the value of getting to try out the concepts that they were learning and actually run the software themselves.

Capabilities of the software: 6 comments. Students listed particular strengths of the software and learning with the software, including the capability to change parameters and run new simulations quickly, producing thorough and clear output, and the complexity that allowed many ways to make mistakes from which one could learn. One comment emphasized that the colors were pleasant and that the interface was friendly. Another like the ease with which the error analysis section could be reported.

Visualization of results: 17 comments. All 17 commented on the benefit of being able to visualize the flow and/or contours and seeing this as helpful.

Miscellaneous negative comments: 8 comments. Two respondents mentioned that they already had CFD experience and didn't benefit much from this introduction. Others thought this experience was too complicated, too brief, or would not generalize to other settings where they had to use the real software. One commented that the obtained results were not accurate.

Students at Site III also had the opportunity to respond to the question: "What needs to be improved in the CFD lab to maximize its value to you? Forty one students out of a total of 81 respondents provided comments. Two raters categorized the comments into the following four categories.

Technical aspects: 8 comments. Four respondents complained that their grids did not converge. Others mentioned that the software was buggy, requested better post processing and resizing techniques, and commented that the "saving" procedure was tricky.

Instruction and Teaching: 26 comments. These respondents provided numerous suggestions for improvement, including better trained and more knowledgeable TAs, better instructions and instruction booklets, more tutorials on CFD, a more vigorous approach with more time spent, perhaps in a workshop but not in this course, better explanations of how variables affect the output, more emphasis in lab reports and more time spent on learning the principles.

Time Issues: 7 comments. All six requested that more time be spent on CFD. One said if more time cannot be allocated then don't include it at all.

Miscellaneous: 3 comments. Two stated that they preferred to learn Fluent rather than Flowlab. One commented on the lack of student control and wanted to do more than just plug in numbers.

Evaluation Conclusions The evaluation results indicate that considerable progress has been made toward developing implementations that accomplish some of the learning goals. In addition, the implementation is improved in numerous ways over the Year One efforts. In spite of this improvement, there remain numerous areas where the Flowlab implementation can be improved for the majority of students like these. These possible areas of improvement are outlined below.

One important characteristic to be explored in future data collections is the variability in student responses. Students varied greatly in their appreciation of the CFD experience, with some reporting considerable growth and learning and others reporting frustration and lack of benefit. Future data collections will examine how the students who express benefit from the CFD experience are different from students who are frustrated and do not seem to benefit from the CFD component. It may be that the implementation can only be improved so much and that some students will continue to benefit while others do not. The fact that this variability exists across the three varied sites suggests that it is not an artifact or one pool of learners but is rather characteristic of fluid dynamics courses more generally. Future studies will investigate and report the student characteristics that correlate with benefiting from the CFD lab/component compared with characteristics of those students who do not benefit.

Conclusions and Future Work

Project is successful in development of CFD educational interface for pipe, nozzle, and airfoil flows, including design for teaching CFD methodology and procedures, implementation based on site testing at partner universities with different courses or laboratories, applications, conditions, exercise notes, and evaluations. Site testing indicates versatility of CFD educational interface since courses and pedagogy different at different universities, which suggests wider applicability of CFD educational interface at diverse universities. Evaluation indicates areas of strength as well as strategies for improvements and more effective implementation. Future work will focus on the following improvements. (1) Develop improved user interface: dynamic sketch window, import and export data, etc., reports (convergence histories, separate monitoring convergence from diagnostics results), diagnostics capabilities and graphics, including verification and validation. (2) Develop extensions for additional active options and advanced level (See Fig. 10 and Fig. 11). (3) Develop extensions for more general wider applications CFD templates: for internal (pipe, transition, low and high speed, heat transfer, noncircular cross section) and external (2D, 2D unsteady, 3D, 3D unsteady) flow. (4) Develop extensions for student individual investigation/discovery. (5) Use smaller lab groups with emphasis *hands-on* activities and remote access via college computer labs and Internet. (6) Perform implementation (with improvements) and site testing and evaluation. (7) FLUENT will disseminate current TM.

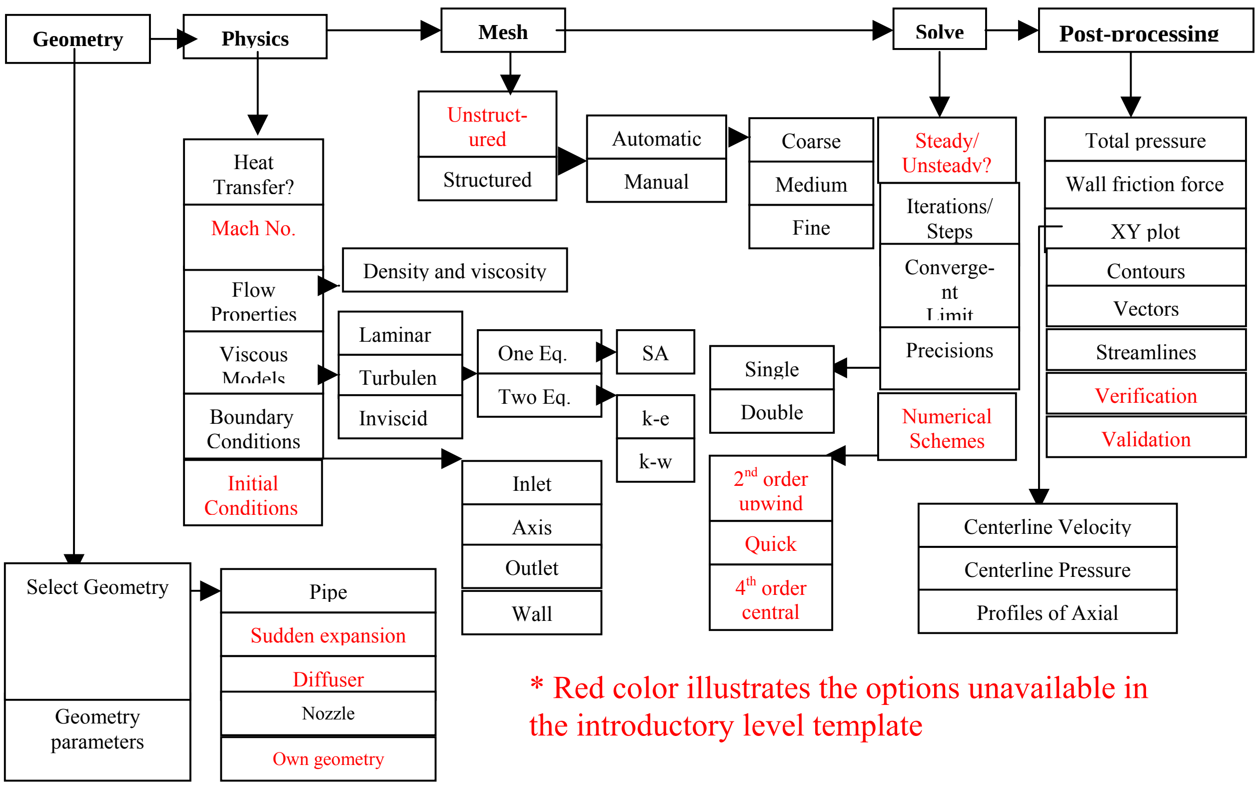

Fig. 10. Flow chart for combined 2D axisymmetric advanced internal flow template*

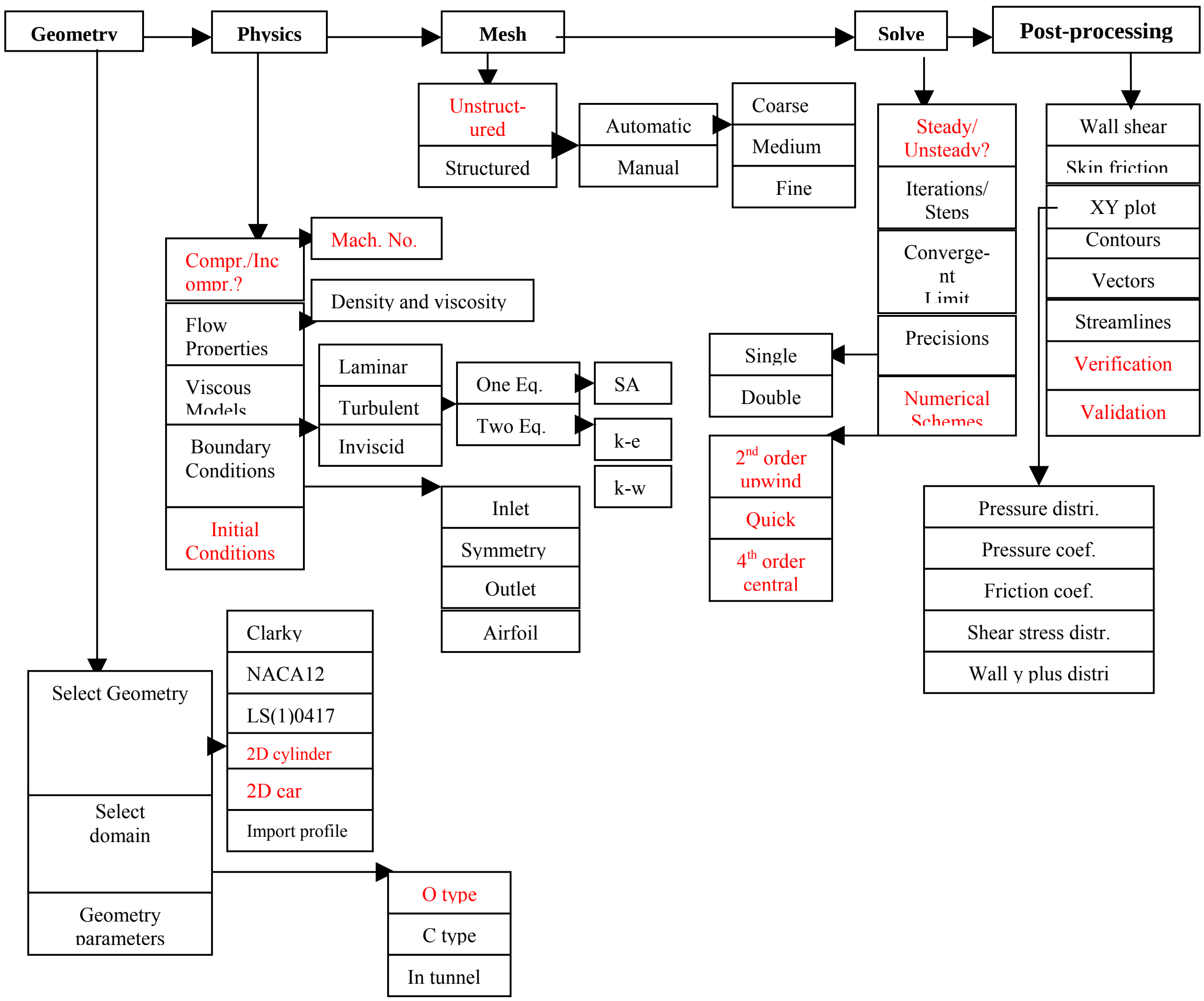

Fig. 11. Flow chart for combined 2D advanced external flow template

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