Integration of simulation technology into undergraduate engineering courses and laboratories

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Abstract: Teaching modules for complementary computational and experimental fluid mechanics and uncertainty analysis were developed to integrate simulation technology into undergraduate engineering courses and laboratories. Engineering faculties from a range of public and private universities and the software partner Fluent, Inc. have collaborated to develop, implement, evaluate, and disseminate web-based teaching modules utilising simulation technology based on further development of the commercial software, FlowLab. The first two years' formative and summative student evaluation data identified successful leaning outcomes, as well as strategies for improvement, including the need for an efficient, hands-on, 'computational fluid dynamics educational interface' to better simulate engineering practice.

Keywords: simulation technology; teaching module; computational fluid dynamics; experimental fluid dynamics; uncertainty analysis.

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1 Introduction

In major research universities, the undergraduate engineering curriculum is changing in response to rapid advancements in simulation technology. This paper assumes that simulation based design and virtual reality will supplement and eventually replace experimental observations and analytical methods in engineering practice. It is reasonable to expect that a major shift will occur in how the scientific method forms a basis of conceptual truth, a shift from reliance on observations, based on experiments, to reliance on logic and experimentally confirmed prior principles used to create valid simulation systems. These changes will take place as engineering becomes a more global discipline with its procedures subject to international standards. In this view, engineering simulation technology will cover a broad range of uses: for example, from computerised systems (Pomeranz, 1996; Cheng and Chen, 1999; Das, 1999; Wankat, 2002) to solutions of physics based initial boundary value problems. The work described in this study focuses on the latter; specifically on computational fluid dynamics. Computational fluid dynamics is a widely used tool in fluids engineering with many specialty and commercial codes covering many specific disciplines world wide. One major obstacle in using computational fluid dynamics is lack of trained users.

Recently, engineering educators have begun integration of computational fluid dynamics into undergraduate fluid mechanics and senior design courses, using both specialty and commercial codes (Young and Lasher, 1995; Navaz et al., 1998; Hailey and Spall, 2000). In a few cases, computational fluid dynamics was combined with experimental fluid dynamics laboratories (Henderson et al., 1999; Olinger and Hermanson, 2001). At the same time, experimental fluid dynamics laboratories have undergone improvements for modern measurement systems (Shih et al., 1999; Ting, 1999) and use of standard uncertainty analysis procedures (Steele et al., 1997; Stern et al., 1999). Additionally, rapid changes in software learning systems and internet technology have impacted teaching through Web based instruction (Higuchi, 2001; Devenport et al., 2005; Militzer et al., 2000), remote experiments (Pniower et al., 1999), studio model courses (Ribando et al., 2001), electronic text books (Caughey and Liggett, 1998), and distribution via CD-ROM (Homsy, 2001).

In summary, the present project concerns integration of simulation technology into undergraduate engineering courses and laboratories through the development of teaching modules for complementary computational fluid dynamics, experimental fluid dynamics, and uncertainty analysis**.** Knowledge of all three is essential along with optimisation methods for realisation of physics based, simulation based design. The teaching module includes three parts:

- lectures on computational fluid dynamics and experimental fluid dynamics methodology and standard procedures and uncertainty analysis
- computational fluid dynamics templates for academic use of commercial industrial computational fluid dynamics software
- exercise notes for the use of computational fluid dynamics templates and complementary experimental fluid dynamics and uncertainty analysis.

The commercial industrial computational fluid dynamics software is FlowLab http://www.fluent.com/, which is widely used in many industries and universities and is a partner in the project. Initial teaching modules are based on those developed as 'proof of concept' at The University of Iowa from 1999 to the present, as updated and currently being used http://css.engineering.uiowa.edu/~fluids/. Recently, the project expanded under sponsorship National Science Foundation Course, Curriculum and Laboratory Improvement – Educational Materials Development Program to include 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 teaching module, effective implementation, evaluation, dissemination, and pedagogy of simulation technology utilising web based techniques. The evaluation is conducted through collaboration with faculty from The University of Iowa, College of Education, Department of Psychology and Quantitative Foundation and Center for Evaluation Assessment. The present paper describes the overall objectives, approach, results, and conclusions based on the first two years' efforts.

2 Development of teaching modules

Simulation based design must be physics based to gain credibility and wide spread use. The research and development process involves complementary computational fluid dynamics, experimental fluid dynamics and uncertainty analysis; therefore, teaching modules are developed to mirror this process. However, teaching modules are also developed so that computational fluid dynamics, experimental fluid dynamics, and uncertainty analysis components can be used separately or even as inclass demonstrations.

Fluid mechanics courses are an important area for investigation and development because they are included in the curricula of most engineering programmes with both programme-required and technical-elective courses. Programme-required courses are at both the introductory and intermediate levels, whereas technical elective courses are usually at intermediate levels. Often introductory level courses are required by more than one programme (e.g., mechanical, civil, and bio engineering departments). Most introductory courses are text book based with emphasis on analytical fluid dynamics with or without experimental fluid dynamics. Experimental fluid dynamics is used primarily to demonstrate flow physics with limited consideration of experimental fluid dynamics methodology and uncertainty analysis. Because of its difficulty and the lack of practical learning tools for students, computational fluid dynamics is seldom included. Intermediate level courses are either analytical fluid dynamics with or without computational fluid dynamics and/or experimental fluid dynamics assignment or experimental fluid dynamics including methodology and in some cases, uncertainty analysis.

This collaboration is developing teaching modules to meet all these situations, but with the recommendation that they be used in complementary fashion. Although the initial focus is on teaching modules for introductory level courses, the collaboration intends to develop applications at the intermediate level as well. Teaching modules are intended to be aids that supplement but do not replace faculty lectures. Faculty are expected to provide appropriate background discussion depending on course level and implementation and use the teaching module as complementary aids, especially for detailed learning of procedures for complementary computational fluid dynamics, experimental fluid dynamics, and uncertainty analysis laboratory assignments. The design of the teaching modules emphasises the qualities of ease of use, especially for undergraduate students, and easy integration into current usual classroom and laboratory teaching materials for undergraduate fluid mechanics courses and laboratories.

The specific teaching modules focus on applications related to pipe, airfoil, nozzle, and cylinder flow for use in required introductory fluid mechanics and thermal/fluid, gas dynamics and aerodynamics laboratory courses. The labs are designed for hands-on seamless teaching of computational fluid dynamics methodology and procedures as *tools* of engineering practice, while at the same time relating results to fluid physics and classroom lectures. Table 1 summarises the teaching module used in the introductory fluid mechanics course at The University of Iowa.

Table 1 Teaching module used for introductory fluid mechanics course: computational fluid dynamics (CFD), experimental fluid dynamics (EFD) and uncertainty analysis (UA) Lab materials

Lecture	*Other docs*	*Lab1: viscosity*	*Lab 2: pipe flow*	*Lab 3: airfoil*
EFD lecture	EFD UA report	Prelab1	Pre EFD Lab2	Prelab3
	EFD UA theory	EFD 1	EFD Lab2	EFD Lab3
	EFD UA example	Lab1_UA	Lab2_UA	Benchmark data
	Lab report instructions	Instructions_UA	Instructions_UA	Instructions_UA
CFD lecture	CFD lab report instructions	None	Pre CFD Lab1	Pre CFD Lab2
	Sample report		CFD Lab1	CFD Lab2

All lectures, problem solving, and the experimental fluid dynamics, computational fluid dynamics, and uncertainty analysis labs followed a shared set of overlapping goals. The goals were developed in accordance with ABET principles, and used as guidelines for course and laboratory development, implementation, and evaluation.

The goals of the experimental fluid dynamics, computational fluid dynamics, and uncertainty analysis laboratories are to teach students methodology and procedures through classroom lectures and the use of modern facilities (pipe stands, wind tunnels), measurement systems (load cells, pressure transducers, sensors and computerised data acquisition and reduction), classroom lectures, and use of commercial computational fluid dynamics software (FlowLab) for complementary, experimental and computational laboratories, including teamwork and presentation of results in written and graphical form. The focus is on hands-on experiences with computational fluid dynamics, experimental fluid dynamics and uncertainty analysis as 'tools' for solving fluid mechanics problems, including validation using benchmark experimental fluid dynamics data and uncertainties, analysis of results regarding fluid physics, and the enhancement of and deepening of learning from classroom lectures. The recognition of the need for hands-on involvement grew out of students' evaluation survey comments during Year One of the collaboration. The goal is for the hands-on activities to deepen and activate the more passive learning that takes place in classroom lectures.

Experimental fluid dynamics lectures provide extensive information and cover basic experimental fluid dynamics philosophy, types of experiments, test design, data reduction equations, measurement systems and uncertainty analysis. Spreadsheets are provided to the students to facilitate their uncertainty analysis. Assignments cover the purpose of the analysis, test design, data reduction equations, measurement systems, data acquisition and reduction procedures, uncertainty analysis and use benchmark data and the analysis and discussion results. As might be expected, adequate institutional investment in facilities, measurement systems, and support staff is essential for meeting the goals of the experimental fluid dynamics and uncertainty analysis laboratories.

Computational fluid dynamics lectures cover the definition and use of computational fluid dynamics, modelling, numerical methods, and computational fluid dynamics processes, including geometry, flow conditions and properties, models, initial and boundary conditions, grid generation, numerical parameters, solution, post processing, and uncertainty analysis. Assignments cover the purpose, simulation design, and applications of the computational fluid dynamics process. Similarly, institutional investment in appropriate software is essential for meeting goals of computational fluid dynamics and uncertainty analysis laboratories. Computational fluid dynamics labs were designed for each lab to build on previous lab assignments in sequence to achieve greater depth in each step of the computational fluid dynamics process such that, at intermediate levels, students approach the expertise needed for engineering practice. It is best for students to use commercial industrial software, as they likely will use it as professionals; however, students also need a learning interface to facilitate the transition to expert application of the computational fluid dynamics process. Faculty and Fluent Inc. are collaborating on the development of learning interface.

3 Collaboration

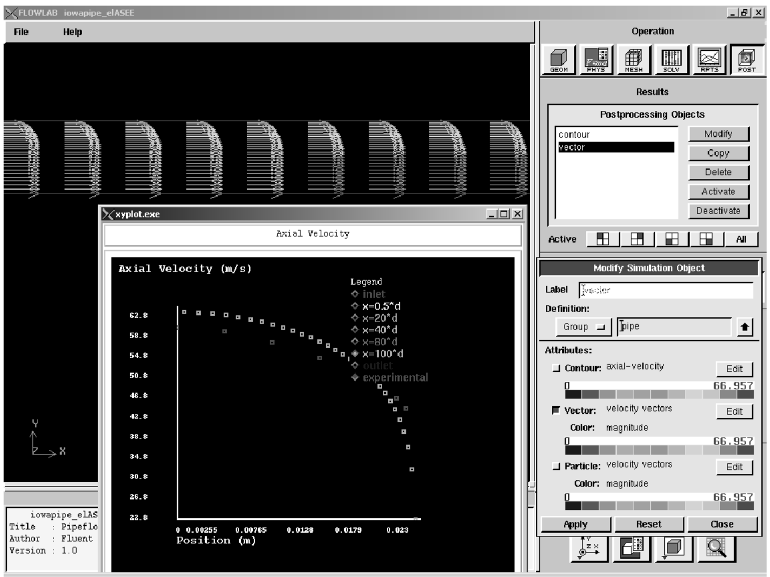
3.1 Faculty

Faculty meetings are held for discussions on further development teaching module, effective implementation, evaluation, dissemination, and pedagogy of simulation technology utilising web based techniques. Different faculty took primary responsibility and expert reviews for each of the teaching module and experimental fluid dynamics, computational fluid dynamics, and uncertainty analysis lecture notes. The pipe and airfoil teaching module will be site tested at as many of the different universities as possible using common evaluation plan. Project activities are summarised on the project web site http://www.iihr.uiowa.edu/~istue/.

3.2 Fluent

In collaboration with the project faculty members, Fluent, Inc. is developing the computational fluid dynamics templates for academic use of commercial industrial software used in the present project are being developed by Fluent under product name ‘FlowLab’, with collaboration faculty. FlowLab http://www.flowlab.fluent.com/ is a computational fluid dynamics based educational software package, which allows students to solve predefined exercises. Initially, templates and exercise notes are being developed for pipe, airfoil, nozzle, and cylinder flow to be used in teaching introductory level courses and laboratories. Figure 1 shows the template for pipe flow at specific steps of computational fluid dynamics process. Pedagogy for templates is to both teach and provide students with hands-on experience with computational fluid dynamics process. Buttons in the upper right hand corner take students through the computational fluid dynamics process: geometry, physics (flow conditions and properties, modelling, initial and boundary conditions), mesh, solve (numerical parameters), reports (iterative convergence), and post processing (flow visualisation, analysis, verification, validation using imported experimental fluid dynamics data and uncertainties). Button options are predefined for student exercises using a hierarchy system whereby introductory levels have fewer options and intermediate levels, more options such that by the third level, students are essentially using FLUENT.

Figure 1 Computational fluid dynamics template for pipe flow



4 Implementation

The projects were implemented in the context of an introductory fluid mechanics course at Iowa, an aerodynamics and ‘gas dynamics laboratory’ courses at Iowa State, a required fluid mechanics sequence at Cornell, and an aerodynamics course at Howard.

4.1 Iowa

The introductory level fluid dynamics course at Iowa is a four semester hour junior level course required in Mechanical and Civil and Environmental Engineering and frequently elected by Biomedical Engineering students. Traditionally, the course included four lectures per week for analytical fluid dynamics with a few additional experimental fluid dynamics labs for the purpose of highlighting fundamental principles. After being reviewed and revised, the course was restructured to provide three semester hours of analytical fluid dynamics (3 lectures per week) and one semester hour (1 laboratory meeting per week) of complementary experimental fluid dynamics, computational fluid dynamics, and uncertainty analysis laboratories.

To meet the revised educational goals, faculty and staff created a sequence of computational fluid dynamics, experimental fluid dynamics and uncertainty analysis labs (Table 1). Labs were intended for hands-on seamless teaching of computational fluid dynamics, experimental fluid dynamics, and uncertainty analysis methodology and procedures as *tools* of engineering practice while at the same time relating results to fluid physics and classroom lectures. Table 1 provides an overview of the computational fluid dynamics lab with complementary experimental fluid dynamics lab materials. During the first week of class, one classroom lecture provides an overview of analytical fluid dynamics, experimental fluid dynamics and computational fluid dynamics as complementary *tools* of fluids engineering practice, which is followed throughout the semester by the analytical fluid dynamics and problem solving lectures and experimental fluid dynamics, computational fluid dynamics and uncertainty analysis labs. Students work in groups, but submit separate lab reports.

The class web site distributes all the lab materials. Lab report instructions guide students to write lab reports, which constitute 25% of the final grade. Different sections of lab report instructions are cross referenced to the Lab goals, so students' performances in the lab report can be used to provide evidence of students' skill and knowledge acquisition related to the lab goals. Students are required to hand in answers to Prelab questions to encourage their familiarity with lab materials before coming to the lab. Experimental fluid dynamics Prelabs are used to familiarise students with specific purpose, test design, measurement system and procedures, uncertainty analysis, and data analysis and discussion for each experimental fluid dynamics lab. In computational fluid dynamics Prelabs, students are asked to learn how to run FlowLab following the computational fluid dynamics process, be familiar with the software interface and run simpler simulation problems (laminar pipe and inviscid airfoil flows). In computational fluid dynamics Labs, students study more complicated problems (turbulent pipe and airfoil flows). Exercise notes of computational fluid dynamics labs are designed to encourage students' own investigations and discoveries by providing different options, related to modelling and numerical methods.

4.2 Iowa state

Iowa State University conducted the implementations for the 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 analytical fluid dynamics while the labs are used as experimental fluid dynamics testbeds for certain concepts introduced in the class. Computational fluid dynamics through the FlowLab software was introduced in the first two labs Aerodynamics I Lab and Gas Dynamics Lab as part of the NSF project. Aerodynamics I Lab is a half a semester course and specifically discusses the following four concepts:

Concept 1. *Streamlines, streak lines and path lines (analytical fluid dynamics) and their connection to flow visualisation*. A smoke tunnel is used in the experimental fluid dynamics lab to visualise flow over two dimensional and three dimensional objects in the lab. FlowLab is introduced in this lab as a demonstration by the instructor.

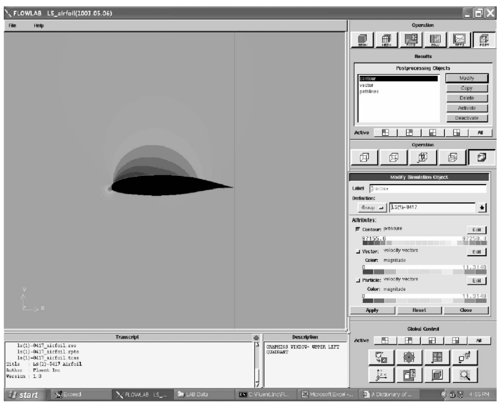
Concept 2. As an application of the Bernoulli's equation taught in the theory, class a closed circuit wind tunnel is calibrated in the experimental fluid dynamics lab.

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 2D cylinder is observed and contrasted with the potential flow solution. Computational fluid dynamics use is required in this lab. The students are required to conduct the same experiments numerically using FlowLab and compare analytical fluid dynamics, experimental fluid dynamics and computational fluid dynamics results in the reports they write.

Aerodynamics I and the associated lab Aerodynamics I Lab are introductory courses and are sophomore level classes. 'Computational fluid dynamics' 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 computational fluid dynamics through FlowLab. However, they are not required to know the details of the computational fluid dynamics theory.

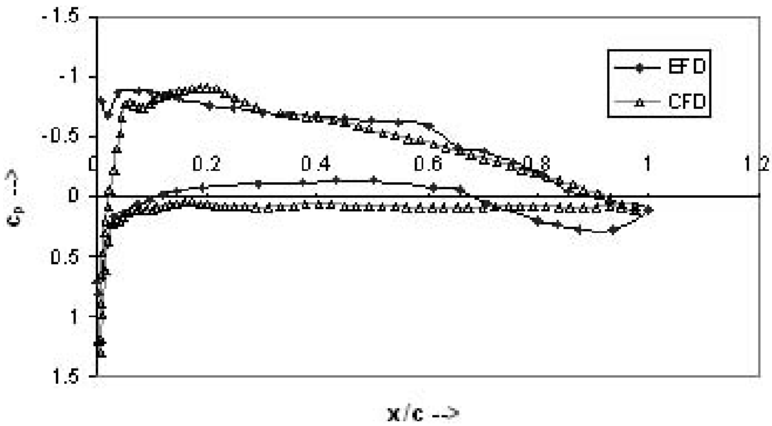
Concept 4. The final lab involves the aerodynamic characteristics of an airfoil using pressure measurement. FlowLab is used to conduct the same experiments numerically; a pressure measurement comparison with experimental fluid dynamics is presented in the following illustrations (Figures 2 and 3).

Figure 2 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.

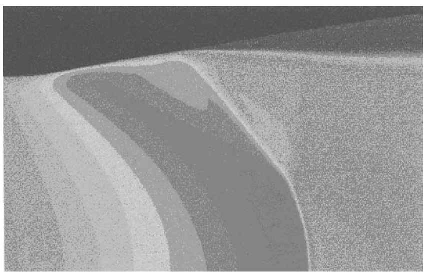
Figure 3 Cp distributions over LS(1)-0417 airfoil



The 'gas dynamics laboratory' at Iowa state university. The gas dynamics laboratory taught at Iowa State University is a juniorlevel 0.5 credit hour course which complements a 3 credit hour lecture course. The three lab experiments are: a tabletop Schlieren experiment for natural convection, time evolution of tank pressure and temperature in a tank blowdown, and wall pressure measurements for different shock positions within a nozzle which is connected to the tank.

The shock image which students see in the experiments is often quite different from an idealised normal or oblique shock. Real shocks can be highly curved and may have 'λ-shock' patterns, such as those seen in Figure 4, due to the interaction of the shock with the boundary and shear layers. One of the main goals of introducing computational fluid dynamics in this lab is to create a bridge between idealised theory and the realistic shock patterns seen in experiments. The computational fluid dynamics is presented in two short lectures applied in exercises assigned as homework. The first homework is a guided tutorial. The second homework is a more openended use of FlowLab and comparisons with the analysis and experiment.

Figure 4 Typical Mach number contour for a λ-shock using FlowLab



The FlowLab template for the nozzle is designed to use three meshes with varying degrees of mesh density, including boundary layer stretching. As expected, the viscous solutions show the desired λ-shock behaviour seen in Figure 4. It should be noted that while the FlowLab template provides adequate resolution at low pressure ratios, the template could not grid resolve solutions at high pressure ratios for the short run times desired.

4.3 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. 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 the heated condition only, with operation at the unheated condition dropped.

In the first week of the lab for each student group, the instructor introduced the experimental setup 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. In the second week, data processing was discussed in a recitation session. Students were provided with a handout on the computational fluid dynamics solution process and operating details of running FlowLab. This handout has been 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 1,00,820 is shown in Table 2. 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 2 Typical results for the pipe flow lab at Cornell University

	Experiment	*Simulation*	*Correlation*
Friction factor	0.0180 ± 0.003	0.0168	0.0177
Nusselt number	185	192	183

The pipe flow template enabled students to visualise velocity vectors and the temperature fields 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 modelling 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.

Close collaboration with Fluent Inc. personnel insured that the pipe flow template met the requirements at Cornell. Our experience was that small groups were well suited to introducing students to computational fluid dynamics basics through FlowLab. The FlowLab experience resulted in many students showing an enthusiasm for learning more about computational fluid dynamics.

4.4 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 computational fluid dynamics and error analysis. The students then used the templates and FlowLab in openended 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 after incorporation of the experimental fluid dynamics component of the project. However, informal, formative evaluations demonstrated 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.

5 Evaluation

The evaluation component provided information for both formative and summative uses (Frechtling, 2002; Scriven, 1991). During the first semesters of the project, major staff efforts were directed to developing and refining the teaching modules, lecture notes, laboratories and student experiences. Evaluation data collected from learners included regular classroom evaluations, tailored student surveys and informal discussions. In addition, the instructors reviewed lab reports and test results to be sure that students were successfully learning the content and skills. This initial formative evaluation produced the following conclusions.

According to the instructors, most students' performance was very good. They appeared to be cooperative and eager to learn. Students reported appreciation for the hands-on experimental fluid dynamics and uncertainty analysis labs, including use of facilities that allowed them to relate their results to *reallife* applications. Students also appreciated any hands-on learning processes in the computational fluid dynamics labs using a step by step method through the software interface, which enhanced their understanding of the computational fluid dynamics process to analyse and solve practical fluids' engineering problems. However, analysis of student responses also suggested several ways to improve implementation. For experimental fluid dynamics and uncertainty analysis, respondents suggested the following improvements, including:

- the use of smaller lab groups and more workstations so that all students could experience direct involvement with experiments
- the use of lab time more effectively by eliminating PreLabs and allowing students more time to actually perform their own experiments
- the improvement of the experimental fluid dynamics lecture and lab materials and instruction, especially uncertainty analysis, which needed better instruction and more concise instructions and lab reports
- the improvement of the teaching assistant's grading of lab reports, which was viewed as not providing evaluation information about different categories as required by the lab report instructions

- improvements to the experiments themselves for generality (e.g., pipe transitions and alternative external flow geometries)
- creating greater depth in certain steps of the experimental fluid dynamics process such as use of LabView and advanced laser based measurement systems.

For computational fluid dynamics and uncertainty analysis labs, students also had the following suggestions:

- make the FlowLab interface more user friendly
- combine the computational fluid dynamics and experimental fluid dynamics lab reports and improve teaching assistants' lab reports grading
- design a more interactive and effective use of PreLab and Lab time
- create more access to FlowLab to provide more hands-on experiences.

Once these improvements were addressed, the evaluation component for the next cohorts of student learners also added a focus on student outcomes. Student learners responded to independent, anonymous survey items asking them to judge their own learning of specific instructional components in retrospective fashion, a method with investigated and documented validity for low stakes judgements (Lam and Bengo, 2003). These retrospective judgements focused on specific skills, problem solving abilities and knowledge items regarding experimental fluid dynamics, computational fluid dynamics, uncertainty analysis and general conceptual knowledge and problem solving related to course goals. Students compared their ability to do these tasks or use this knowledge prior to the course and after learning in the course. Because their responses did not affect their grades in the course and were collected anonymously, previous research suggests good validity for these selfevaluations in determining course outcomes (Lam and Bengo, 2003). In addition, the students also responded anonymously to survey items providing evaluations of all the separate implementation components. Finally, the students were encouraged to comment on how to improve the efficiency and effectiveness of the implementation, especially the hands-on components.

Students responded anonymously to the scaled items during the last week of class, indicating their degree of agreement or disagreement on a six point Likert type scale ranging from 'strongly agree' (scored as 6) to 'strongly disagree' (scored as 1) scale. Students also provided openended comments about specific components of the learning experience, which were aggregated, analysed, and summarised. Complete versions of the surveys as administered are available as PDF files at the following website: http://www.iihr.uiowa.edu/~istue/.

5.1 Results for the Site I (University of Iowa)

At Site I, the instructors and teaching assistants conducted an informal lab report analysis to investigate the goal attainment of students as demonstrated in their lab reports, resulting in the following tabled results.

Tables 3 and 4 present the percentage of students at Site I whose lab reports indicated that specific instructional goals had been achieved for both computational and experimental fluid dynamics labs.

Table 3 Percentages of computational fluid dynamics lab reports providing evidence of specific goal attainment, as judged by the course instructor and teaching assistants

Goals	*Student performance*		*Report sections*
	Lab 1	*Lab 2*	
Provide students with hands-on experience with computational fluid dynamics methodology (modelling and numerical methods) and procedures through a step by step approach, following computational fluid dynamics process: geometry, physics, mesh, solve, reports, and postprocessing	96%	96.5%	Total
Students will be able to apply computational fluid dynamics process through the use of educational interface for commercial industrial software to analyse practical engineering problems	100%		3
Students will be able to conduct numerical uncertainty analysis through iterative and grid convergence studies	N/A		4
Students will be able to validate their computational results with experimental fluid dynamics data from their complementary experimental laboratories	100%		3,4
Students will be able to analyse and relate computational fluid dynamics results to fluid physics and classroom lectures, including teamwork and presentation of results in written and graphical form	91%		4,5

Table 4 Percentages of experimental fluid dynamics lab reports providing evidence of specific goal attainment, as judged by the course instructor and teaching assistants

Goals	*Student performance*			*Report sections*
	Lab 1	*Lab 2*	*Lab 3*	
Provide students with hands-on experience with experimental fluid dynamics methodology and uncertainty analysis procedures through a step by step approach following experimental fluid dynamics process: setup facility, install model, setup equipment, setup data acquisition using LabView, perform calibrations, data analysis and reduction, uncertainty analysis, and comparison with computational fluid dynamics and/or analytical fluid dynamics results	91.5%	94%	94.8%	Total
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	29/30	29/30	29/30	2,3
Students will be able to implement experimental fluid dynamics and uncertainty analysis for practical engineering experiments	15/15	15/15	15/15	4
Students will be able to use experimental fluid dynamics data for validation of computational fluid dynamics and analytical fluid dynamics results	36/40	37.5/40	37/40	5,6
Students will be able to analyse and relate experimental fluid dynamics results to fluid physics and classroom lectures, including teamwork and presentation of results in written and graphical form				

Students at Site I also responded to a tailored end of course survey containing 49 Likert type items and 18 supply type items.

The Likert type items were categorised into five clusters addressing the following topics:

- *General learning needs met by the course* (24 items, for example: "My learning needs were well met in this course")
- *Hands-on aspects of the computational fluid dynamics component* (2 items: "The hands-on aspects of the computational fluid dynamics lab helped me learn valuable skills and knowledge")
- *Skills and knowledge gained using the computational fluid dynamics component* (11 items: "As a result of my learning in the computational fluid dynamics lab, I am able to use FlowLab for solving laminar and turbulent pipe flow and inviscid and viscous airfoil flow")
- *Hands-on aspects of the experimental fluid dynamics component* (2 items: "The hands-on aspects of the experimental fluid dynamics lab helped me learn valuable skills and knowledge")
- *Knowledge and skill gained using the experimental fluid dynamics component* (10 items) "As a result of my learning in the experimental fluid dynamics lab, I am able to relate experimental fluid dynamics results to fluid physics and classroom lectures").

The internal consistency reliability estimates (Cronbach, 1951) of the cluster scores ranged from 0.96 to 0.85, indicating good internal consistency, more than adequate for investigating mean group scores and using these measures to document outcomes.

Table 5 presents the means and standard deviations for each of the 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 5 Cluster score means μ and standard deviations σ

Scale	*N cases*	*N items*	μ	σ	*Min*	*Max*
Learning needs overall	55	24	4.56	0.65	2.81	5.63
Hands-on computational fluid dynamics	55	2	3.44	1.36	1.00	6.00
Knowledge, skills, computational fluid dynamics	55	11	4.40	0.93	2.00	6.00
Hands-on experimental fluid dynamics	55	2	4.21	1.13	1.00	6.00
Knowledge, skills, experimental fluid dynamics	55	10	4.55	0.93	1.20	6.00

As can be seen in Table 5, respondents on average 'mildly to moderately' agreed that their overall learning needs were met ($\mu = 4.56$ out of a possible 6.0, $\sigma = 0.65$) and 'mildly to moderately' agreed that their knowledge and skills improved as a result of the computational fluid dynamics lab ($\mu = 4.40$, $\sigma = 0.93$) and experimental fluid dynamics lab ($\mu = 4.55$, $\sigma = 0.93$). Students 'mildly' agreed that the handon experimental fluid dynamics helped them learn ($\mu = 4.21$, $\sigma = 1.13$). However, students on average were not in agreement with statements about the quality of the hands-on experience in the computational fluid dynamics lab ($\mu = 3.44$, between 'mildly agree and mildly disagree', $\sigma = 1.36$). 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 computational fluid dynamics implementation efforts were effective for them.

In response to the openended question, "In your own words, what are the best things about learning with the computational fluid dynamics lab?" respondents reported that they were gaining useful, new knowledge and understanding (10 responses) and liked the hands-on aspects (7 responses), the quality of the software capabilities, the visualisation of results (14 comments) and the teaching/instruction (7 comments).

In response to the openended question, "What are the best features of the experimental fluid dynamics lab and what worked especially well for you?", respondents reported that they liked the tangible and real world aspects (30 comments), teaching/instruction (3 comments), and data acquisition and analysis (5 comments).

In response to the question, "What needs to be improved in the computational fluid dynamics lab to maximise its value to you?" students mentioned needed improvements in technical aspects of the software (7 comments), better organisation of instruction (30 comments) and the need for increased individual access and use (10 comments).

In response to the question, "What needs to be improved in the experimental fluid dynamics lab to maximise its value to you?" students mentioned the need for increased access and individual use (14 comments) and better organisation of instruction (29 comments).

5.2 Site II (Iowa State University) results

At Site II, for purposes of this report, the Likert type survey items were categorised into clusters addressing the following three topics.

- *General learning needs met by the course*: (23 items, for example: "My learning needs were well met in this course")
- *Knowledge and skills acquired through the computational fluid dynamics component*: (12 items: "computational fluid dynamics taught me things that I could not learn through experimental fluid dynamics or analytical fluid dynamics alone")
- *Quality of the hands-on components*: (2 items: "The hands-on aspect of the computational fluid dynamics lab worked well for me").

As at Site I, cluster score reliability estimates ranged from 0.95 to 0.89, indicating a high level of internal consistency reliability.

As can be seen in Table 6, respondents on average 'mildly to moderately' agreed that their overall learning needs were met ($\mu = 4.20$ out of a possible 6.0, $\sigma = 0.85$) and 'mildly to moderately' agreed that their knowledge and skills improved as a result of the computational fluid dynamics lab ($\mu = 4.62$, $\sigma = 1.07$). In addition, students on average mildly agree that the quality of the hands-on experience in the computational fluid dynamics lab either helped them learn valuable skills and knowledge or worked well for them (μ = 4.14, σ = 1.06). Variability in cluster scores was great, with some students appearing to be well satisfied while others appeared to be in strong disagreement that these computational fluid dynamics implementation efforts were effective for them.

Table 6 Cluster score means μ and standard deviations σ

Scale	*N cases*	*N items*	μ	σ	*Min*	*Max*
General learning needs	29	23	4.20	0.85	2.12	5.65
Computational fluid dynamics knowledge and skills	29	12	4.62	1.07	1.00	5.63
Hands-on computational fluid dynamics	29	2	4.14	1.06	1.00	5.50

Students also responded to open ended survey items elaborating on their evaluations of the computational fluid dynamics labs. In response to the question: "In your own words, what about the computational fluid dynamics component worked especially well for you or was especially beneficial to you?" students mentioned the quality of the hands-on component (6 comments), the value of the visualisation of results (9 comments), and ease of use (5 comments).

In response to the question, "In your own words, what about the computational fluid dynamics component should be changed the next time it is taught? What needs to be improved?" students mentioned changes to technical aspects (8 comments) and changes to instruction and teaching (13 comments).

5.3 Results from the Site III (Cornell University) implementation

The survey administered at Site III was shorter than the other surveys and only addressed the computational fluid dynamics 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 computational fluid dynamics labs, I am able to" and continued with such statements as "present results from computational fluid dynamics simulations in written and graphical form," or "run FlowLab and implement computational fluid dynamics process for laminar and turbulent flow". The average over all items for 77 of 80 responding students was 4.16 (σ = 1.15), indicating that students, on average, 'mildly agreed' with these statements. The strongest agreement (μ = 4.63, σ = 1.16) was for the item, "… I am able to appreciate that simulation involves approximations and tradeoffs". The least agreement (μ = 3.68, σ = 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.

In response to the question: "In your own words, what are the best things about learning in the computational fluid dynamics lab?", students reported increases in knowledge and understanding (15 comments), the quality of the hands-on aspects (6 comments), the capabilities of the software (6 comments) and visualsation of results (17 comments).

In response to the question: “What needs to be improved in the computational fluid dynamics lab to maximise its value to you?” students reported improvements necessary in technical aspects (8 comments) and instruction and teaching (26 comments), and that more time be spent on computational fluid dynamics.

5.4 Evaluation conclusions

The evaluation results indicate that considerable progress has been made towards developing implementations that accomplish many of the learning goals. In addition, the implementations have improved in numerous ways over the first two years. In spite of this improvement, there remain numerous areas where the FlowLab implementation can be improved for many of the students.

One important characteristic to be explored in future data collections is the variability in student responses. Students varied greatly in their appreciation of the computational fluid dynamics 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 computational fluid dynamics experience are different from students who are frustrated and do not seem to benefit from the computational fluid dynamics 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 artefact of 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 computational fluid dynamics lab/component compared with characteristics of those students who do not benefit.

6 Conclusions and future work

In conclusion, this project has achieved some success in the integration of simulation technology into undergraduate engineering courses and laboratories and in developing, implementing, and evaluating the teaching modules for introductory level fluid mechanics courses and laboratories. The implementation of the developed teaching modules at different universities suggests the versatility of the computational fluid dynamics software interface, since courses, pedagogy, students, emphases, and supporting curricula are different. The experience from this collaboration has resulted in a group of generalised templates with the same “Computational Fluid Dynamics Educational Interface”.

Evaluation results suggest areas of strength as well as strategies for improvements and more effective implementation. Anonymous responses suggest that many students agree that experimental fluid dynamics, computational fluid dynamics, and uncertainty analysis labs were helpful to their learning fluid mechanics and important ‘tools’ that they may need as professional engineers. Students, on average, ‘mildly to moderately’ agreed that their overall learning needs were met. They appreciate the hands-on experience, but would like the learning experience to be as hands-on as possible.

Future work will focus on site testing along with improvements to the introductory level teaching module in conjunction with initial development of an intermediate level teaching module. Experimental fluid dynamics and uncertainty analysis labs will be improved for increased student hands-on involvement, for example, through student installation of model and measurement systems also making the uncertainty analysis more interesting and through students performing calibrations. Computational fluid dynamics and uncertainty analysis labs will be improved through development of a "Computational Fluid Dynamics Educational Interface", allowing more student options and transition from an introductory to an intermediate level computational fluid dynamics template. Such improvements are expected to increase student benefit and enthusiasm. Final versions of teaching modules will be disseminated by FLUENT Inc.

This collaborative approach, followed for integration of computational fluid dynamics into undergraduate fluid mechanics courses and laboratories, should also be useful for integration of simulation technologies for other disciplines into their respective curricula. The need and importance of integrating computer assisted learning and simulation technology into undergraduate engineering courses and laboratories will have far reaching impact on learning technology and only increase as simulation based design and ultimately virtual reality become increasingly more important in engineering practice.

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