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Hands-on integrated CFD educational interface for introductory fluids mechanics

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Abstract: The development, implementation, and evaluation of an effective curriculum for students to learn integrated computational fluid dynamics (CFD) and experimental fluid dynamics (EFD) is described. The CFD objective is to teach students CFD methodology and procedures through a step-by-step CFD process using a CFD educational interface for hands-on student experience. The EFD objective is to teach students use of modern facilities, measurement systems including ePIV and Flowcoach, and uncertainty analysis (UA), following a step-by-step EFD process for fluids engineering experiments. Students analyse and relate CFD and EFD results to fluid physics and classroom lectures, including teamwork and presentation of results. Implementation is described based on results for an introductory level fluid mechanics course, which includes integrated CFD and EFD laboratories for the same geometries and conditions. An independent evaluation investigates and reports the learning outcomes and the effectiveness of the CFD educational interface, ePIV, Flowcoach and CFD and EFD laboratories.

Keywords: hands-on labs; integrated CFD and EFD; CFD educational interface; CFD process; EFD process; ePIV; Flowcoach; uncertainty analysis; course evaluation.

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1 Introduction

It is well understood that the use of interactive learning is an important part of an engineering education (Feisel and Rosa, 2005). As technology grows and advances it provides new opportunities for well-rounded and meaningful classroom and laboratory student experiences. Multiple studies have found that computer modelling, electronic learning modules, and hands-on experiments lead to an increase in student understanding when applied to engineering courses (Fraser et al., 2007; Keith et al., 2008; Okamoto et al., 2009; Budny and Torick, 2010). For example, Okamoto et al. (2009) developed a novel thermal management of electronics course that combined a standard lecture with both computer modelling and hands-on experiments. They found that students showed a significant improvement in their understanding of the topics, as well as an increase in their ability to confidently perform related tasks. Likewise, Keith et al. (2008) found that using electronic modules was a successful method for teaching chemical engineering students about fuel cells.

This use of technology has often been applied to fluid dynamics courses, where the use of experimental fluid dynamics (EFD) and computational fluid dynamics (CFD), either alone or in combination, have led to improved student understanding (Fraser et al., 2007; Budny and Torick, 2010; Stern et al., 2006; Sert and Nakboglu, 2007; Van Ransbeeck et al., 2009). An example of this is Fraser et al. (2007) who found that students showed significant improvement in areas they found most difficult when a computer simulation was used to help explain the concepts. Van Ransbeeck et al. (2009) used a combination of EFD and CFD methods, which allowed students to successfully learn fluid dynamic theories by using a hands-on approach and comparing this to computational models. Such experiences not only help students learn about fluid dynamic theories, but also start to build skills that can be applied in future careers in research or industry, as CFD is becoming a widely used tool. As proposed by Stern et al. (2006) CFD interfaces that are developed as learning tools can help students transition into using more complex codes once they are in industry. The goal of combing these tools is to prepare students to solve real world fluid dynamics problems, improve understanding and gain hands-on skills.

Herein the development, implementation, and evaluation of an effective curriculum for students to learn integrated CFD and EFD including ePIV and Flowcoach in introductory undergraduate level courses and laboratories are described. The CFD objective is to teach students from novice to expert users who are well prepared for engineering practice using a CFD educational interface for hands-on student experience, which mirrors actual engineering practice (Stern et al., 2006). The EFD objective is to teach students use of modern facilities, measurement systems, and uncertainty analysis (UA) following a step-by-step approach, which mirrors the real-life EFD process: setup facility; install model; setup equipment; setup data acquisition; perform calibrations; data acquisition, analysis and reduction; and UA, and comparison CFD and/or analytical fluid dynamics (AFD) results (Stern et al., 2004a). Implementation is described based on results of an introductory level fluid mechanics course, which includes integrated CFD and EFD laboratories for the same geometries and conditions. An collaborative (internal and external) evaluation (Yarbrough et al., 2011) investigates and reports the learning outcomes and the effectiveness of the CFD educational interface, ePIV/Flowcoach and CFD and EFD laboratories. Stern et al. (2006) describes development, implementation, and evaluation of the CFD educational interface in intermediate level courses.

2 Introductory fluids course with EFD and CFD laboratories

2.1 Design

The introductory fluid mechanics course at the University of Iowa is a four-semester-hour course, offered as a requisite course to junior level Mechanical Engineering and Civil and Environmental Engineering students and often elected by Biomedical Engineering students. Typically about one hundred students are enrolled in the course each semester. The course consists of classroom lectures and labs. Lectures use textbooks and lecture notes, along with problem solving, with emphasis placed on AFD. Labs include both computational CFD and experimental EFD and ePIV/Flowcoach labs designed to be complementary with each other, as shown in Table 1.

Table 1 Complementary EFD/CFD/UA labs and lab concepts

Labs	*Fluid property TM*	*Pipe flow TM*	*Airfoil flow TM*
EFD labs	*Viscosity experiment:* kinematic viscosity and mass density measurements for glycerin	*Pipe experiment:* flow rate, friction factor, and velocity profile measurements for smooth and rough pipes	*Airfoil experiment:* surface pressure distribution, wake velocity profile, and lift and drag forces measurements for a Clark-Y airfoil model
	• Definition of 'EFD process'	• Comparison between automated and manual data acquisition systems	Using LabView for setting test conditions and data acquisition
	• Data reduction equation	• Measurement systems using pressure tap, Venturi-meter, and pitot probe	• Calibration of loadcell
	• Estimates of errors and uncertainties	• Automated data acquisition using LabView	• Measurement of lift and drag forces with loadcell
	• Bias, precision, and total uncertainty	• The importance of non-dimensionalisation and comparison of results with benchmark data	• Measurement of pressure distribution and velocity profile for an airfoil model
CFD labs	No lab.	*Pipe simulation:* friction factor and velocity profiles for laminar and turbulent pipe flows	*Airfoil simulation:* flow velocity and pressure fields and streamlines around a Clark-Y airfoil geometry
		• Definition of Reynolds number and its value to distinguish laminar and turbulent flows	• Inviscid vs. viscous flow
		• Definition of 'CFD process'	• Boundary conditions
		• Boundary conditions	• Effect of angle of attack on flow field
		Comparison of normalised axial velocity profile for laminar and turbulent pipe flows	• Effect of turbulent models on flow field
		Developing vs. developed	• Validation using EFD data
		Validation using EFD for turbulent pipe flow	
ePIV/ Flowcoach labs	*Cylinder flow:* flow streamline visualisation around a circular cylinder model	*Step flow*: flow rate and average velocity for a step-up model	*Airfoil flow*: velocity field and flow streamlines around Clark-Y airfoil model (miniature)
	• PIV camera settings and visualisation of streamlines	• PIV image correlation parameters and PIV data reduction	• PIV data post-processing using Tecplot software

The present course is founded on a long history of fluid mechanics education at the University of Iowa. Before 1985, the course was mainly textbook-based classroom lectures (four lectures per week) with focus on analytical solution methods and a few experimental labs for highlighting fundamental principles. Subsequently, a wind tunnel was designed and constructed for research quality experiments using modern measurement systems along with complementary student-run potential-flow panel code for comparison with their experimental data, which had favourable learning outcomes and student responses. The concept was expanded during the 1990s by restructuring the course for three-semester hours of AFD (three lectures per week) and one-semester hour (one laboratory meeting per week) for complementary EFD, CFD, and UA laboratories. EFD labs were improved and UA was introduced. Complementary CFD labs were also introduced using an advanced research code modified for limited user options. From 1999 to 2002, the research CFD code was replaced by the commercial CFD software (FLUENT) and refinements were made and the overall approach was used as a proof of concept for the initiation of a three-year National Science Foundation sponsored Course, Curriculum and Laboratory Improvement – Educational Materials Development project Integration of Simulation Technology into Undergraduate Engineering Courses and Laboratories (ISTUE) with faculty partners from colleges of engineering at Iowa, Iowa State, Cornell and Howard universities along with industrial (commercial CFD) partner FLUENT Inc. The ISTUE project focused on the development of a common CFD educational interface and teaching modules (TM) for its use for the faculty partners' respective courses and laboratories. Evaluations confirmed that the implementation was successful but at same time indicated directions for improvements. Students anonymous responses suggested that they agreed the EFD, CFD, and UA labs were helpful for learning fluid mechanics and important tools that they may need as professional engineers in the future; however, they would like their learning experience to be as hands-on as possible. During 2003, additional improvements were made for hands-on complementary EFD/CFD/UA labs. Hands-on is defined as the use of EFD, CFD, and UA engineering tools in meaningful learning experiences, which mirror as much as possible the real-life engineering practice. The most recent improvement was made during 2008 to 2010 by adding complementary ePIV/Flowcoach experiments to the EFD labs.

As a first course in fluid mechanics it provides an introduction to basic concepts in fluid statics, kinematics, and dynamics. Control volume and differential equation and dimensional analysis methods are derived and used to demonstrate applications to simple external- and internal-flow fluids engineering systems to determine variables of interest (pressure; shear stress; velocity distributions; flow rates; forces; energy losses; power requirements; etc.). Homework assignments, tests, and complementary experimental and CFD (EFD and CFD) laboratories are integrated into the course to reinforce the theory and its practical application. The EFD laboratories introduce fluids engineering facilities, measurement systems (equipment and data acquisition and reduction methods) and uncertainty assessment methodology and procedures. The CFD laboratories introduce fluids engineering simulation-based design methods, utilising the CFD educational interface. Three TM's were developed for complementary EFD and CFD labs: fluid property (EFD only) and pipe and airfoil flow (EFD and CFD). Concepts were developed for classroom lectures and the EFD and

CFD labs. The classroom lecture concepts are cross-referenced to the homework and exams.

TM consists of the lab purpose and concepts, educational materials, lab report instructions, pre-lab questions, lab lecture, exercise notes and data reduction sheets for each EFD and CFD lab. For the fluid property TM, the purpose is hands-on student experience with table-top facility and simple measurement system for fluid property measurement, including comparison manufacturer values and rigorous implementation standard EFD UA. For the pipe flow TM the purpose is hands-on student experience with complementary EFD, CFD, and UA for introductory pipe flow, including friction factor and mean velocity measurements and comparisons benchmark data, laminar and turbulent flow CFD simulations, modelling and numerical methods and verification studies, and validation using AFD and EFD. For the airfoil TM the purpose is hands-on student experience with complementary EFD, CFD, and UA for introductory airfoil flow, including lift and drag, surface pressure, and mean and turbulent wake velocity profile measurements and comparisons benchmark data, inviscid and turbulent flow simulations, modelling and numerical methods and verification studies, and validation using AFD and EFD.

2.2 Course and problem solving learning objectives

The course general learning objectives are listed in Table 2. Eight objectives were developed based on the classroom lecture and EFD and CFD lab concepts covering the student's learning experience, complementary EFD and CFD laboratories, student evaluation and class website. The end-of-semester survey is used for assessment. The problem solving learning objectives are listed in Table 3. Seven objectives were developed based on the class room lecture concepts covering basic definitions, fluid statics and dynamics, control volume and differential analysis, dimensional analysis, and applications for internal and external flows. Homework, quizzes, exams and the survey are used for assessment. The assessment techniques and instruments as well as analysis procedures as summarised in Tables 2 through 6 are described more fully in Section 6, Assessment and Evaluation.

2.3 Implementation

The class website (http://www.engineering.uiowa.edu/~fluids/) provides all course materials, including lecture notes, EFD and CFD lab handouts and assignments, and grades for homework, laboratory reports, and tests. Lectures present website lecture notes, etc. with additional discussion, using an overhead projector. Students should not take detailed in-class notes copying this material since it is available and can be downloaded and printed via the website, but should rather augment website material with notes based on additional discussion, which supplement and expand on website material.

Table 2 Course general learning objectives and evaluation

	Objectives	*Assessment technique*	*Quantitative data on student performance (on a scale of 10)*										
			'02	*'03*	*'04*	*'05*	*'06*	*'07*	*'08*	*'09*	*'10*	*Avg*	*SD*
1	Students in general will enjoy their learning experience in this course	Survey	7.9	8.2	n/a	n/a	n/a	8.2	7.5	7.0	6.7	*7.6*	*0.6*
2	Experimental fluid dynamics (EFD), computational fluid dynamics (CFD), and uncertainty analysis (UA), classroom and pre-lab lectures will effectively prepare students for 'hands-on' laboratory experience.	Survey	6.7	6.5	n/a	n/a	n/a	8.8	7.8	7.1	7.4	*7.4*	*0.8*
3	'Hands-on' laboratory experience will use EFD, CFD, and UA as engineering tools in a meaningful learning experience.	Survey	n/a	6.4	n/a	n/a	n/a	8.5	8.0	7.5	7.8	*7.6*	*0.7*
4	'Hands-on' laboratory experience will mirror as much as possible the 'real-life' engineering practice.	Survey	n/a	n/a	n/a	n/a	n/a	8.8	7.2	6.9	7.1	*7.5*	*0.8*
5	The lab content and skill development will effectively match students' learning needs, including prior knowledge and skill, student objectives for self-development as engineers, and student dispositions and learning styles.	Survey	7.7	7.3	n/a	n/a	n/a	9.0	7.4	7.3	7.1	*7.6*	*0.6*
6	Students' evaluation through homework, tests, and pre-lab and laboratory reports will be fair, accurate, proper, feasible, and useful.	Survey	8.0	8.2	n/a	n/a	n/a	8.8	7.7	7.9	7.6	*8.0*	*0.4*
7	Evaluations in this course will allow students to show what they know and can do, as related to expected course outcomes.	Survey	7.9	8.0	n/a	n/a	n/a	8.4	7.8	7.5	7.6	*7.9*	*0.3*
8	The website will be useful for learning in this course, including posting class information, news, schedule, lecture notes, EFD/CFD lab materials, homework and test solutions, grades, image gallery, and links.	Survey	9.2	8.7	n/a	n/a	n/a	8.5	8.8	8.5	8.3	*8.7*	*0.3*

Table 3 Problem solving learning objectives and evaluation

Objectives		*Assessment technique*	*Quantitative data on student performance (on a scale of 10)*										
			'02	*'03*	*'04*	*'05*	*'06*	*'07*	*'08*	*'09*	*'10*	*Avg*	*SD*
1	Students will be able to apply the definitions of a fluid and shear stress for solving engineering problems, including use of definitions, tables, and graphs of fluid properties such as density, specific weight and gravity, viscosity, surface tension, compressibility, and vapour pressure.	Survey	8.8	8.7	8.7	8.9	8.7	8.7	8.7	8.4	8.2	*8.6*	*0.2*
		Homework	n/a	8.9	9.6	9.2	9.7	9.6	9.6	9.8	9.6	*9.5*	*0.3*
		Quiz	n/a	n/a	n/a	n/a	n/a	8.9	7.8	8.1	7.7	*8.1*	*0.5*
2	Students will be able to apply the definition of pressure and principles and methods used to solve engineering problems for static fluids.	Survey	8.6	8.6	8.7	8.6	8.2	8.4	8.4	8.0	8.1	*8.4*	*0.3*
		Homework	n/a	9.0	9.5	9.0	9.4	9.3	9.6	9.1	9.4	*9.3*	*0.2*
		Quiz	n/a	n/a	n/a	n/a	n/a	8.4	8.3	6.3	8.1	*7.8*	*0.9*
3	Students will be able to apply the principles and methods used to solve engineering problems with fluids in motion, including definitions and calculation of velocity, volume flow rate, acceleration, and vorticity; and pressure variation for rigid body translation and rotation and Bernoulli equation.	Survey	8.7	8.5	8.3	8.7	8.3	8.5	8.5	8.2	8.3	*8.4*	*0.2*
		Homework	n/a	8.9	9.7	9.1	9.2	9.4	9.7	9.7	9.7	*9.4*	*0.3*
		Quiz	n/a	n/a	n/a	n/a	n/a	8.5	8.0	7.4	7.0	*7.7*	*0.6*
Goals 1 to 3		Exam	n/a	8.8	7.5	7.7	8.4	8.5	8.4	7.8	8.5	*8.2*	*0.5*

Table 3 Problem solving learning objectives and evaluation (continued)

Objectives		*Assessment technique*	*Quantitative data on student performance (on a scale of 10)*										
			'02	*'03*	*'04*	*'05*	*'06*	*'07*	*'08*	*'09*	*'10*	*Avg*	*SD*
4	Students will be able to apply control volume and differential approach for the continuity, momentum, and energy equations solving engineering problems.	Survey	8.6	8.4	8.2	8.2	8.2	8.5	8.3	8.3	7.9	*8.3*	*0.2*
		Homework	n/a	8.1	9.5	9.0	9.1	9.1	9.7	9.5	9.7	*9.2*	*0.5*
		Quiz	n/a	n/a	n/a	n/a	n/a	8.5	7.5	8.2	7.1	*7.8*	*0.6*
5	Students will be able to apply the basic concepts of dimensional analysis and similarity for solving engineering problems, including dimensional homogeneity, Buckingham Pi theorem, and similarity, scaling laws, and model testing.	Survey	7.8	7.8	7.4	7.9	7.9	8.0	8.0	7.8	7.7	*7.8*	*0.2*
		Homework	n/a	8.9	9.7	9.0	9.5	9.4	9.8	9.7	9.8	*9.5*	*0.4*
		Quiz	n/a	n/a	n/a	n/a	n/a	n/a	n/a	4.6	5.7	*5.2*	*0.6*
Goals 4 to 5		Exam	n/a	8.5	8.3	9.2	8.2	8.3	8.3	8.6	7.8	*8.4*	*0.4*
6	Students will be able to apply the concepts and calculation methods for internal flows for solving engineering problems, including friction and minor losses for laminar and turbulent smooth and rough pipe flow.	Survey	7.9	7.8	7.6	8.9	7.8	8.2	8.1	7.6	8.1	*8.0*	*0.4*
		Homework	n/a	8.7	9.8	8.6	8.9	9.6	9.7	9.3	9.7	*9.3*	*0.5*
		Quiz	n/a	n/a	n/a	n/a	n/a	8.5	7.3	7.1	8.3	*7.8*	*0.6*
7	Students will be able to apply the concepts and calculation methods for external flows for solving engineering problems, including boundary layer theory and definition of shear stress and force, velocity profile, and boundary layer thickness for laminar and turbulent flow; use of drag coefficients for calculation of drag for bluff bodies; and use of lift and drag coefficients for calculation of lift and drag of airfoils.	Survey	8.1	8.1	7.6	8.7	7.9	8.3	8.3	7.9	7.7	*8.1*	*0.4*
		Homework	n/a	8.4	9.9	8.8	9.3	9.4	9.7	9.2	9.8	*9.3*	*0.5*
		Quiz	n/a	n/a	n/a	n/a	n/a	8.7	8.2	8.9	6.7	*8.1*	*0.9*
Goals 6 to 7		Exam	n/a	8.2	8.0	8.5	8.3	8.9	8.9	8.4	8.0	*8.4*	*0.4*

A total 44 classroom lectures are given throughout the semester, three lectures per week and each lecture for 50 minutes. One lecture is used for introducing an overview of AFD, EFD, and CFD as complementary tools of engineering practice at the beginning of the course, and one EFD classroom lecture and one CFD classroom lecture are given before the first EFD and CFD labs, respectively. At the beginning of the EFD and CFD lectures students take a pre-test on the EFD and CFD labs, respectively, and take a post-test on the final lecture day. A few example problems are solved during each lecture and two or three homework problems on similar concepts are assigned, due by next lecture day. Office hours by teaching assistants are provided after each lecture to answer students' questions on solving the homework problems. In-class pop-quizzes are given randomly approximately every two weeks and a total about ten quizzes through the semester. There are two in-semester 50-minute exams and one final 120-minute exam. All exams are closed-notes and books but one-page formula sheet is allowed to exams. The final course grade is based on the total score points earned during the semester for homework (10%), quiz (15%), exams (50%), and lab reports (25%). A student anonymous survey is also given on the final day.

3 EFD fluids laboratory

3.1 Design

Engineering EFD testing is undergoing change from routine tests for global variables to detailed tests for local variables for model development and CFD validation, as design methodology changes from model testing and AFD to simulation-based design. Detailed testing requires use of modern facilities with advanced measurement systems following standard procedures and UA. Requirements on intervals of uncertainties are even more stringent than required previously since they are a limiting factor in establishing intervals of CFD validation and code certification and ultimately credibility of simulation technology. Also, routine test data is more likely used 'in-house' whereas detailed test data is more likely utilised internationally, which puts increased emphasis on standardisation of procedures. Detailed testing offers new opportunities, as amount and complexity of testing is increased.

The EFD labs are designed to provide students with hands-on experience with EFD methodology and UA procedures following the EFD Process (Figure 1), which mirrors the real-life engineering practice and guides students smoothly through the labs even for those with less or no experience conducting experiments. The 'EFD Process' is a step-by-step procedure:

1 test setup

2 data acquisition

3 data reduction and analysis

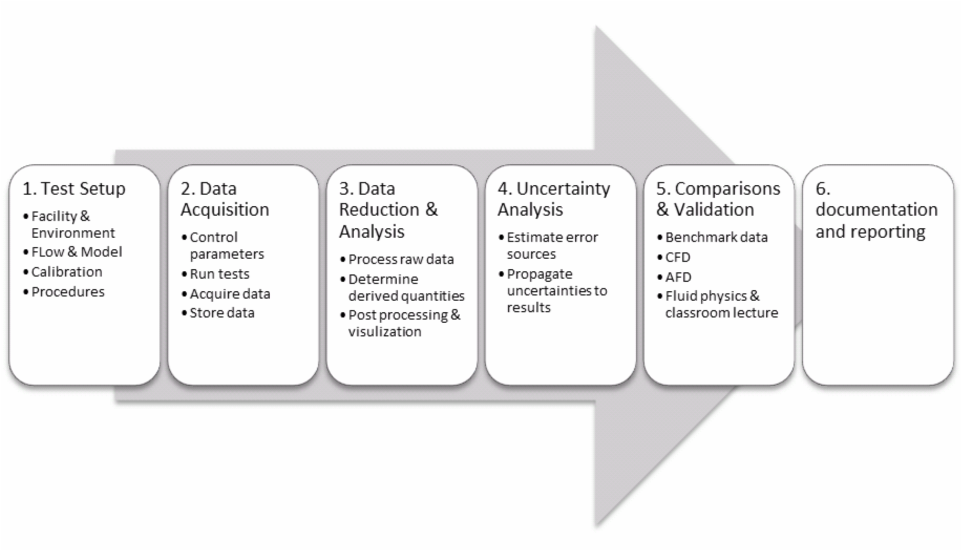
4 UA

5 comparisons and validation

6 documentation and reporting.

The EFD Labs begin with a simple tabletop facility with manual measurement systems and transition to using more complex modern pipe-stand and a wind tunnel test facilities with more advanced measurement systems and automatised data acquisition. The experimental data from the EFD labs are used as benchmark data for the CFD labs.

Figure 1 EFD process



Three EFD labs were developed for the measurements of:

1 density and kinematic viscosity (‘Viscosity experiment lab’)

2 flow rate, velocity profile and friction factor in pipe flows (‘Pipe experiment lab’)

3 pressure distribution and forces acting on an airfoil (‘Airfoil experiment lab’), in conjunction with the complementary EFD and CFD fluid property and pipe and airfoil flow TM’s.

The labs were designed to provide basic EFD concepts. For the viscosity experiment lab, the concepts are the definition of EFD process, data reduction equations, estimates of errors and uncertainties, and bias, precision, and total uncertainty. For the pipe experiment lab, the concepts are comparison between automated and manual data acquisition systems, measurement systems using pressure tap, Venturi-meter and pitot probe, automated data acquisition using LabView, and the importance of non-dimensionalisation and comparison of results with benchmark data. For the airfoil experiment lab, the concepts are the use of LabView for setting test conditions and data acquisition, calibration of loadcell, lift and drag forces measurements using a loadcell, and pressure distribution and velocity profile measurements for an airfoil model.

Table 4 EFD labs learning objectives and evaluation

Objectives	*Assessment technique*	*Quantitative data on student performance (on a scale of 10)*										
		'02	*'03*	*'04*	*'05*	*'06*	*'07*	*'08*	*'09*	*'10*	*Avg*	*SD*
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 calibration, data analysis and reduction, UA, and comparison with CFD and/or AFD results.	Survey	7.6	7.7	8.2	8.3	8.3	8.2	8.1	7.8	7.8	*8.0*	*0.2*
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, loadcells, and computer data acquisition system (LabView) and data reduction.	Survey	8.0	7.8	8.5	8.5	8.3	8.3	8.3	7.5	8.1	*8.1*	*0.4*
3 Students will be able to implement EFD UA for practical engineering experiments.	Survey	7.0	6.8	7.6	7.6	6.6	7.8	7.6	7.0	7.2	*7.2*	*0.5*
4 Students will be able to use EFD data for validation of CFD and analytical fluid dynamics (AFD) results.	Survey	8.2	7.7	8.0	8.3	7.3	8.5	8.4	8.0	8.1	*8.1*	*0.4*
5 Students will be able to analyse and relate EFD results to fluid physics and classroom lectures, including teamwork and presentation of results in written and graphical form.	Survey	7.9	7.9	8.1	8.3	8.0	8.4	8.1	7.6	7.9	*8.0*	*0.3*
Goals 1 to 5	Lab report 1	n/a	n/a	n/a	9.3	8.4	8.7	9.2	8.6	8.9	*8.8*	*0.4*
	Lab report 2	n/a	n/a	n/a	9.0	8.4	9.1	9.0	9.0	8.9	*8.9*	*0.3*
	Lab report 3	n/a	n/a	n/a	9.3	8.8	9.3	8.8	9.0	8.8	*8.9*	*0.2*
	Pre-test	n/a	n/a	n/a	5.3	5.5	5.9	5.8	4.8	5.2	*5.4*	*0.4*
	(Confidence)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	(3.7)	(4.3)	*(4.0)*	
	Post-test	n/a	n/a	n/a	7.8	7.0	7.1	7.9	7.9	7.1	*7.5*	*0.4*
	(Confidence)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	(7.3)	(6.7)	*(7.0)*	
	Score increase	n/a	n/a	n/a	2.5	1.6	1.1	2.2	3.1	1.9	*2.0*	*0.6*

3.2 EFD learning objectives

The learning objectives of EFD labs are listed in Table 4. Five objectives were developed based on the lab concepts (Table 1) covering the EFD process, use of modern facilities and measurement systems, UA and relationship classroom lectures and CFD labs. The lab reports, pre/post-test and end-of-the semester survey are used for assessment.

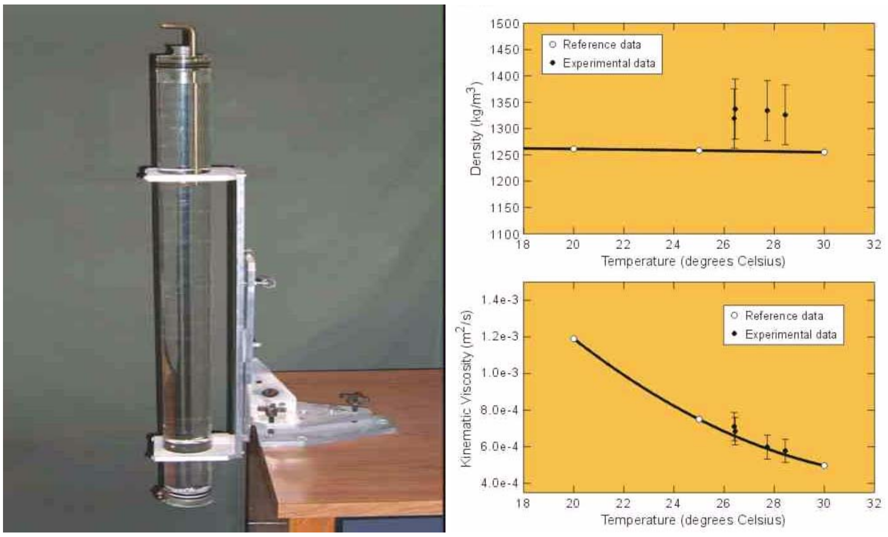
3.3 Implementation

Each EFD lab consists of two laboratory meetings: a pre-lab meeting and a regular lab meeting. Each meeting is for two hours once per week. At the beginning of each lab, a lecture is given for an overview of the experiment: purpose, measurement systems, experimental process, UA methodologies, and relevant fluid dynamics theory. Students are required to read the lecture materials prior to pre-lab meetings and answer the pre-lab questions during the pre-labs in order to familiarise themselves with the lab. Hands-on procedures for the experiment are provided in the exercise notes of each lab. Data reduction sheets (usually Microsoft Excel spreadsheets) are used to facilitate the data analysis and UA. Lab report instructions guide students to write lab reports and can be used by teaching assistants to grade the reports. Students work in groups, typically three to four students, but submit separate lab reports. Specific implementation of each EFD lab is as described below.

Viscosity experiment lab: the purpose of this lab is to measure fluid properties (density and kinematic viscosity of glycerin) by using a table-top facility (Figure 2) and simple measurement devices. Students compare their measurement results with the manufacturer’s values and implement standard EFD UA. The lab lecture is used to provide the background fluids dynamics theories to derive the equations for fluid density and kinematic viscosity. The standard UA methodology and procedures are also emphasised during this lecture. For pre-lab questions, students derive the equations and consider necessary measurement variables and devices, along with discussions on the bias and precision limits of the measurement. The hands-on lab exercise is by following the EFD process:

1. For test setup students prepare a long acrylic-cylinder, filled with glycerin, and several of Teflon or steel spheres.
2. Students drop the spheres to fall freely through the glycerin and measure the sphere falling distance and time, and the sphere diameter and the ambient room temperature as well. Measurements are by using simple devices such as a tape-measure, a stopwatch, a micrometer, and a thermometer.
3. Data reduction is by using the data reduction equations derived during the lab lecture.
4. UA includes estimations of the bias limit by considering the elemental error sources for all measurement variables and the precision limit by repeating the test 10 times, and subsequently the total uncertainty.
5. Students compare glycerin density and viscosity values from their own measurements with the manufacture’s specification along with their UA results.
6. Discuss and report the results.

Figure 2 Table-top facility for the EFD viscosity experiment lab (left) and example outcomes (right) (see online version for colours)



Pipe experiment lab: the purpose of this lab is to provide hands-on experience using a pipe-stand test facility (Figure 3) and modern measurement systems including pressure transducers, pitot probes, and computerised data acquisition with LabView software, to measure flow rate, velocity profiles, and friction factors in smooth and rough pipes, determining measurement uncertainties, and comparing results with benchmark data. The lecture for this lab emphasises the differences between the manual and automatised data acquisition methods and introduces the LabView software. The pre-lab questions are focused on choosing suitable measurement devices for different measurement variables. The hands-on lab exercise for this lab is as following:

1 Test setup is at the pipe-stand that is equipped with pressure taps, a Venturi-meter, and a pitot probe.

2 Data acquisition includes the measurements of static pressure, flow rate, and velocity profile for smooth or rough pipes. The pressure measurements are done in two ways: the first method is manual readings of the manometers whereas the second method is by using a pressure transducer with an automated data acquisition system.

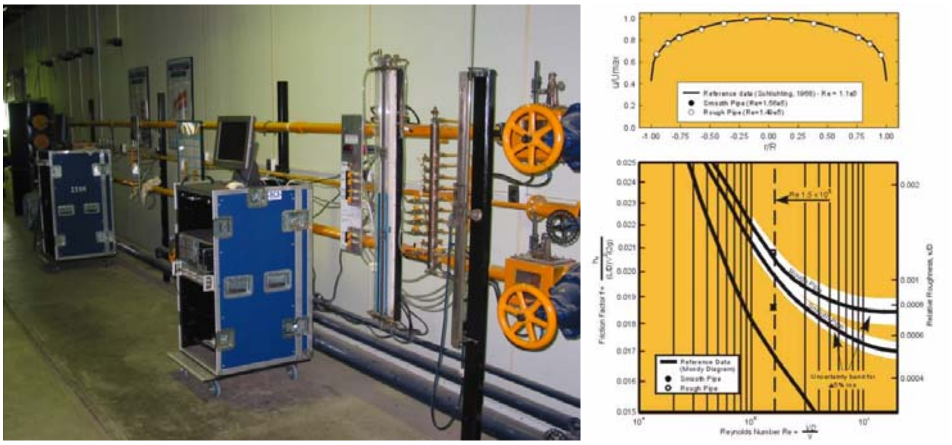
3 Data reduction is for flow Reynolds number, friction factor, and velocity distribution, and the flow rate.

4 For UA, a spreadsheet is provided to help students with the UA procedures. The automated data acquisition system considerably facilitates the repeat measurements that are required for the precision limit estimation of the UA.

5 Students compare friction factor values from their own measurements with the Moody diagram readings from a textbook, and the velocity distribution and flow rate with the benchmark data provided by the instructors.

6 Students report measurement results and the associated uncertainty interval estimations and discuss the agreement with the benchmark data.

Figure 3 Pipe-stand facility for the EFD pipe experiment lab (left) and example outcomes (right) (see online version for colours)



Airfoil experiment lab: The purpose of this lab is to measure the surface pressure distribution, wake axial velocity profile, and lift and drag forces on a Clark-Y airfoil at a wind tunnel facility (Figure 4), and compare the results with the benchmark data including UA. The lab lecture for this lab introduces the concepts related to digital data acquisition systems: calibration, noise, settling time, and sampling time. The pre-lab questions ask students to consider different ways of measuring the lift and drag forces. The hands-on EFD process for this lab is:

1 Test setup is for a Clark-Y airfoil model mounted at the wind tunnel facility with a closed circuit open test section. The control of the wind tunnel is by using a LabView-based automatised control system. The wind tunnel facility is equipped with a pressure transducer, loadcell, pitot probe, and an automatised traverse system. The airfoil model has a total 29 pressure taps located circumferentially along its mid-span.

2 Data acquisition is for two angles of attack, 0° and 16°. Measurements include the air temperature, barometric pressure, free-stream velocity, lift/drag forces, surface pressure, and the axial velocity profile in the wake. Prior to measurements students calibrate the loadcell against a set of standard weights. The free-stream velocity is measured with a pitot probe installed at the upstream of the airfoil at the test section. The surface pressure measurements are at the 29 pressure taps by using a scanivalve and a pressure transducer. The wake velocity profile is by using a pitot probe with attached to an automatised two-axis traverse system.

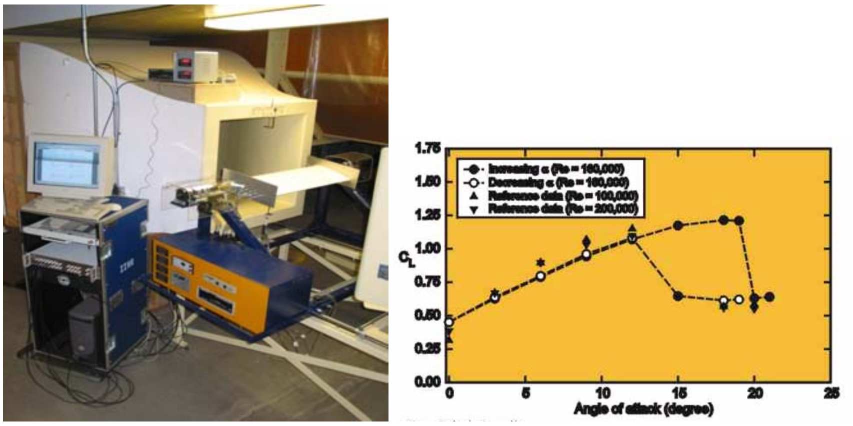
3 Data reduction is for the lift and drag coefficients done in two different ways. The first method is by integrating the measured surface pressure distribution over the airfoil for lift force and by applying the momentum integral method to the measured wake velocity profile data for drag force. The second method is by using the lift and drag force values from direct loadcell measurements.

4 UA is conducted with an aid of the provided spreadsheet.

5 Students first compare the lift and drag coefficients between the two different methods and with the published benchmark experimental data.

6 Students report and discuss the results and the comparisons.

Figure 4 Wind tunnel facility for the EFD airfoil experiment lab (left) and example outcomes (right) (see online version for colours)



4 CFD educational interface and CFD labs

4.1 Design

The CFD educational interface is designed to teach students CFD methodology (modelling and numerical methods) and procedures through hands-on, user-friendly, and interactive implementation for practical engineering applications, while not requiring students' own computer programming. The CFD process (Figure 5) is a step-by-step procedure which guides students smoothly from simulation setup to the final solution of the initial boundary value problem (IBVP) at hand. The CFD process mirrors the actual engineering practice:

1 geometry (solid or fluid boundaries)

2 physics (compressible/incompressible, with/without heat transfer, fluid properties, modelling, initial and boundary conditions)

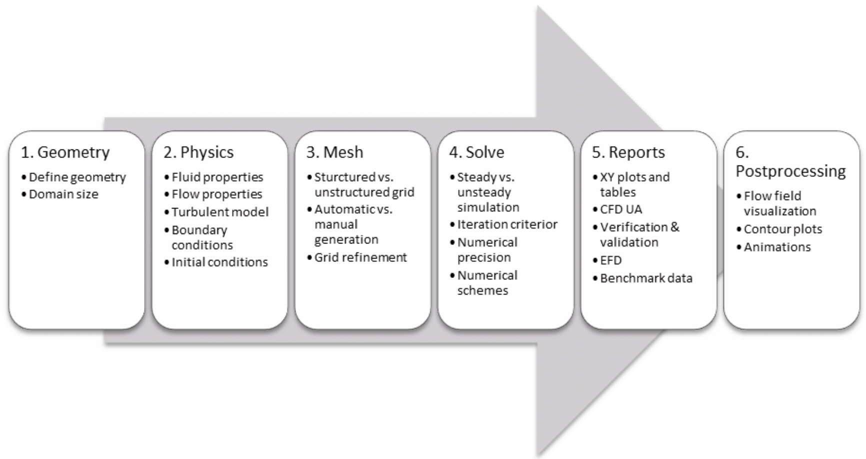
3 mesh specification (structured/unstructured, manual/automatic meshing)

4 solution procedure (numerical parameters, solution convergence monitoring, different numerical schemes)

5 reports

6 post-processing (flow visualisation, analysis, verification, validation using imported EFD data and uncertainties).

Figure 5 CFD process



A hierarchical system of predefined optional menus facilitates the use of exercises and encourages students' self-learning. Enough information is provided to ease the student transition to using the full FLUENT (or any other industrial CFD) code directly. The hands-on CFD educational interface has the following features: User-friendly and interactive interface; follows exactly the CFD process; no requirement for advanced computer language skills; stand-alone application including grid generation, solving, and post-processing; compatible with Microsoft Operating Systems and applications; different depths of CFD templates for introductory and intermediate levels; hands-on interactions with the software using mouse and keyboard input; self-guided studies; powerful and accurate solvers; powerful virtualisation tools; verification; and sketch window for geometry and boundaries.

Two introductory level CFD fluids labs were developed, which are the

1. 'pipe simulation'
2. 'airfoil simulation' labs, constituting the complementary EFD and CFD pipe and airfoil flow TMs.

The 'Pipe Simulation' lab is to simulate turbulent pipe flow. An example screenshot of the CFD educational interface for this lab is shown in Figure 6. The pipe flow conditions are the same as students use for the pipe experiment EFD lab. Students will compute the axial velocity profile, centreline velocity and pressure, and friction factor of the pipe flow from the simulation. Students will also compare simulation results with their own experimental data and analyse the differences between the CFD and EFD results and possible numerical and/or experimental errors. The 'Airfoil Simulation' lab is to conduct parametric studies for turbulent flow around airfoil geometry. An example screenshot of the CFD educational interface for this lab is shown in Figure 7. Students will calculate the lift and drag coefficients of the airfoil at various angles of attack by using several different numerical turbulent models, and will investigate the effects of airfoil angle of attack and numerical turbulence model on their simulation results. Students will also compare simulation results with their own experimental data from the 'Airfoil Experiment' and analyse the differences and possible numerical and/or experimental errors.

Figure 6 Example screenshots of the CFD pipe flow simulation educational interface (see online version for colours)

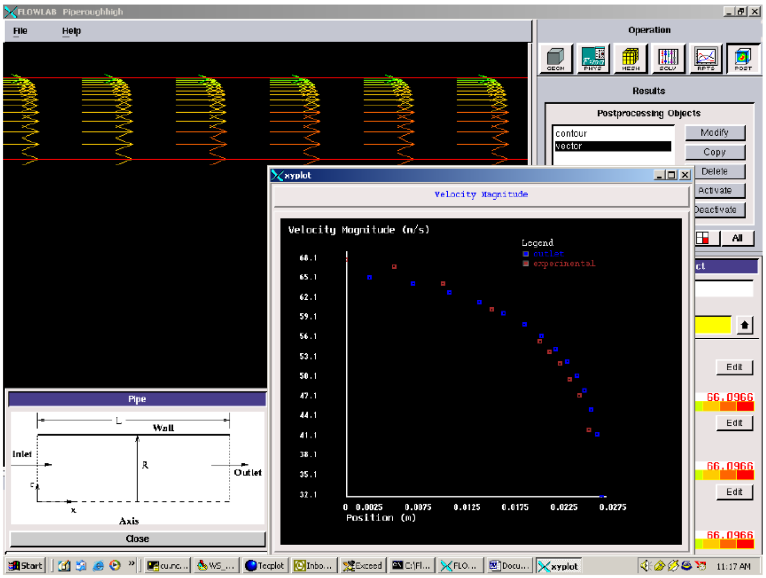
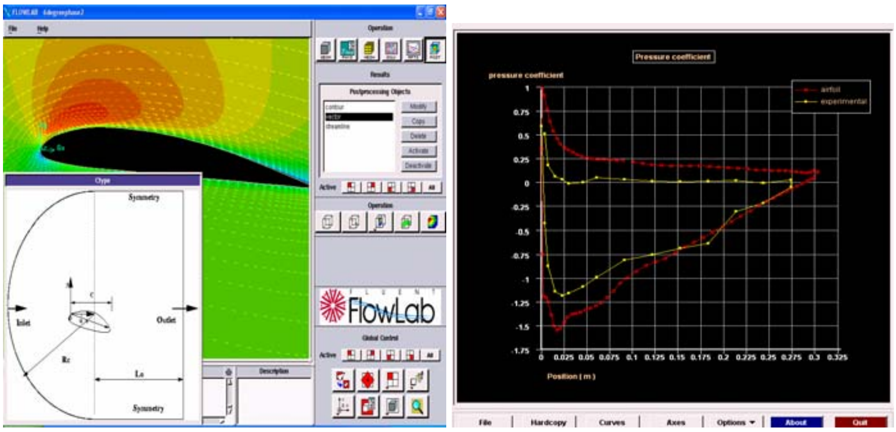


Figure 7 Example screenshot of the CFD airfoil flow simulation educational interface (left) and an example outcome showing comparisons between the CFD and EFD results (see online version for colours)



The CFD labs were designed to provide basic CFD concepts. For the pipe flow simulation the concepts are the definition of the CFD process, boundary conditions (inlet, outlet, wall, axis), iterative and grid convergence, developing length and fully developed velocity profiles of laminar and turbulent flow, effect of single/double precision, verification using AFD for laminar flow, and validation using students' own EFD data for turbulent flow. For the airfoil simulation the concepts are boundary conditions (inlet, outlet, symmetry, and airfoil), pressure coefficient and lift/drag coefficients, inviscid vs. viscous flow, effects of angle of attack, effects of turbulence models, and validation using students' own EFD data.

Table 5 CFD labs learning objectives and evaluation

	Objectives	*Assessment technique*	*Quantitative data on student performance (on a scale of 10)*										
			'02	*'03*	*'04*	*'05*	*'06*	*'07*	*'08*	*'09*	*'10*	*Avg*	*SD*
1	Provide students with 'hands-on' experience with CFD methodology (modelling and numerical methods) and procedures through step-by-step approach following CFD process: geometry, physics, mesh, solve, reports, and post processing.	Survey	7.8	7.3	8.4	8.7	8.5	8.4	8.6	8.0	8.0	*8.2*	*0.5*
2	Help students to learn CFD methodology and procedures through the educational interface.	Survey	n/a	n/a	n/a	n/a	n/a	n/a	8.4	8.4	8.1	*8.3*	*0.2*
3	Students will be able to apply CFD process through use of educational interface for commercial software to analyse practical engineering problems.	Survey	8.0	7.5	8.4	8.6	8.6	8.6	8.1	8.2	8.0	*8.2*	*0.4*
4	Students will be able to conduct numerical uncertainty analysis through iterative and grid convergence studies.	Survey	7.8	7.4	8.1	8.1	8.2	8.0	8.2	8.2	7.9	*8.0*	*0.3*
5	Students will be able to validate their computation results with EFD data from their complementary experimental laboratory.	Survey	7.6	7.5	8.4	8.7	8.3	8.4	8.1	8.3	8.0	*8.1*	*0.4*

Table 5 CFD labs learning objectives and evaluation (continued)

	Objectives	*Assessment technique*	*Quantitative data on student performance (on a scale of 10)*										
			'02	*'03*	*'04*	*'05*	*'06*	*'07*	*'08*	*'09*	*'10*	*Avg*	*SD*
6	Students will be able to setup IBVP through the educational interface, including: 1 create geometry 2 setup fluid properties 3 generate mesh automatically or manually 4 setup appropriate solvers 5 report 6 post-process simulation data.	Survey	n/a	n/a	n/a	n/a	n/a	n/a	8.1	8.4	8.1	*8.2*	*0.2*
7	Students will be able to learn more flow physics beyond the conditions they used in the complementary EFD labs. Students will conduct parametric studies using the educational interface to investigate inviscid vs. viscous flows, effect of turbulent models, effect of angles of attack, and effect of order of accuracies, etc.	Survey	n/a	n/a	n/a	n/a	n/a	n/a	8.1	8.3	8.1	*8.2*	*0.1*
8	Students will be able to analyse and relate CFD results to fluid physics and classroom lectures, including teamwork and presentation of results in written and graphical form.	Survey	7.5	7.1	8.0	8.2	8.0	8.0	8.3	8.3	8.1	*7.9*	*0.4*
	Goals 1 to 8	Lab report 1	n/a	n/a	n/a	9.5	9.2	9.3	9.0	9.0	9.1	*9.2*	*0.2*
		Lab report 2	n/a	n/a	n/a	9.6	9.6	9.5	9.5	9.4	9.4	*9.5*	*0.1*
		Pre-test	n/a	n/a	n/a	5.7	5.7	5.2	4.9	5.1	4.9	*5.2*	*0.4*
		(Confidence)	n/a	n/a	n/a	n/a	n/a	n/a	n/a	(3.3)	(3.3)	*(3.3)*	
		Post-test	n/a	n/a	n/a	7.0	6.6	6.9	7.3	8.1	6.7	*7.1*	*0.5*
		Confidence	n/a	n/a	n/a	n/a	n/a	n/a	n/a	(8.0)	(6.7)	*(7.3)*	
		Score increase	n/a	n/a	n/a	1.4	0.9	1.6	2.4	3.0	1.8	*1.9*	*0.7*

4.2 CFD learning objectives

The learning objectives of the CFD labs are listed in Table 5. Eight objectives were developed based on the lab concepts (Table 1) covering the CFD process, verification and validation, flow physics, and relationship to the classroom lectures and EFD labs. The lab reports, pre/post-test and end-of-the semester survey are used for assessment.

4.3 Implementation

Prior to the beginning of the two CFD labs, one classroom lecture is given presenting the CFD methodology and procedures in general. The CFD lectures cover what, why, and where is CFD used; modelling; numerical methods; types of CFD codes; the CFD process; an example; and an introduction to the CFD educational interface and student applications. For each CFD labs, detailed exercise notes guide students step-by-step on how to use the educational interface to achieve specific objectives for each lab, including how to input/output data, what figures/data need to be saved for the lab report, and questions that need to be answered in the lab report. CFD lab report instructions guide students step-by-step through how to present their results and findings in written and graphical form. Lectures and exercise notes are distributed through the class website. The CFD Lab report covers the purpose and design of the simulation, the CFD process, data analysis and discussion, and conclusion.

Students' hands-on simulation procedures for the CFD labs follow the 'CFD process':

1. Geometry: students can create various geometries and domains including pipe and airfoil. Students need to input different parameters for the particular class of geometry they have selected, such as pipe radius and length and airfoil 'O'/'C' mesh topology, chord length, angle of attack.

2. Physics: students need to choose whether to model the flow as compressible/incompressible, with/without heat transfer, as inviscid/viscous, and as laminar/turbulent; set up the fluid properties (density, viscosity, specific heat, thermal conductivity); select appropriate turbulence models, if appropriate; and define boundary conditions (inlet, outlet, symmetry, wall, axis) and initial conditions.

3. Mesh: both structured and unstructured meshes are available. When using structured meshes the student either automatically or manually generates the desired meshes. Automatic meshing is designed for novice/introductory level students. By specifying 'coarse,' 'medium,' or 'fine' meshes, the educational interface will automatically generate a mesh of the corresponding grid density using parameters hard-coded in the software. Manual meshing is designed for intermediate/professional level students.

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

5 Reports: after the iterative solution process converges, all the integral parameters of the solution, such as total forces and lift/drag coefficients, are reported. Various XY plots and verification and validation functions are also available for students to validate their simulations using benchmark, or their own, EFD data, and to conduct CFD UA. The total reduction in magnitude of solution residual and the final level of solution residual are used to determine stopping criteria for the iterative solution process. For unsteady flows, the time history of integral variables (e.g., drag force) is used to determine the degree of convergence of the iterative solution. Grid uncertainty is analysed using two meshes generated by the automatic function of the interface (coarse and medium, or coarse and fine). Grid refinement ratio can also be used to create different sets of meshes.

6 Post-processing: powerful tools can be used to visualise and examine the flow field, such as contours (total/static pressure, velocities, turbulent kinetic energy, temperature, Mach number), vectors, streamlines, and animations.

5 ePIV/Flowcoach laboratory

5.1 Design

The ePIV and Flowcoach systems (Figure 8) are educational versions of the particle image velocimetry (PIV) for flow visualisations and measurements, developed by the Interactive Flow Studies Corporation (http://www.interactiveflows.com/). PIV is a widely used image-based flow field measurement method and has become a very powerful technique for studying fluid mechanics. In general, a PIV system consists of a number of scientific digital cameras and class-IV level high-powered lasers, which are usually expensive and classified as hazardous, thus may not be affordable or adequate for general educational use at typical classrooms or laboratories. In contrast, the ePIV or the Flowcoach system is compact-sized, low-cost, and safe for use, intended to be used as an educational tool. The ePIV consists of a digital camera (600 × 480 pixels with 30 fps), a small laser (class-III, 15 mW green continuous diode), an optical lens, a small water pump, a seed water reservoir, and a small water channel module, which are all secured and covered in a small box housing. Various shaped flow model-inserts (25 mm × 30 mm) are easily replaceable inside the water channel module. The inserts can be made with a rapid prototyping system, can be machined from metal or acrylic, or can be moulded. The Flowcoach system is the 2nd generation of the ePIV system. The Flowcoach system consists of similar components as the ePIV system, but an open system without a cover or a housing. The Flowcoach system uses an LED illumination instead of a laser and bigger size flow model-inserts (80 mm × 80 mm). The ePIV system is for laminar flows only whereas it is possible to visualise laminar, transition and turbulent flows (up to Re = 25,000) with the Flowcoach system. A higher resolution and faster speed camera can be mounted on Flowcoach which will allow PIV analysis of turbulent flows. Both ePIV and Flowcoach systems use the FLOWEX^{TM} software (http://demo.interactiveflows.com/) for camera control, image acquisition, and PIV analysis. The FLOWEX^{TM}'s internet access capability was used for remote diagnostic purposes with the Interactive Flow Studies. By virtue of its strong flow visualisation capability, the ePIV/Flowcoach system can support the present EFD labs and allow students for more active and stronger learning experience.

Figure 8 The ePIV (left) and Flowcoach (right) systems (see online version for colours)

Three ePIV/Flowcoach labs were designed:

1 'cylinder flow'

2 'step flow'

3 'airfoil flow' labs.

The learning concepts used for the cylinder flow lab include PIV camera setting and flow streamlines visualisation. Students learn how to control ePIV/Flowcoach hardware such as camera focus and image brightness best for flow visualisations. The concepts used for the step flow lab are the PIV image correlation parameters and PIV data reduction. Students learn how to use the FLOWEX^{TM} software and determine the necessary parameter values for PIV images processing. The concept used for the airfoil flow lab is the PIV data post-processing. Students learn various data post-processing techniques for the flow field data obtained from the ePIV/Flowcoach system.

The ePIV/Flowcoach labs were also designed to be integrated easily into the complementary CFD and EFD fluid property and pipe and airfoil flow TM's. The flow pattern around the cylinder model from the cylinder flow lab helps students for a better understanding of the flow around the falling sphere from the EFD viscosity experiment lab. The concepts such as the mass conservation, volume flow rate, or the average velocity through a channel learned from the step flow lab can be shared with the EFD pipe flow experiment lab and with the CFD pipe flow simulation lab. Lastly, the ePIV/Flowcoach measured flow field data around an airfoil model from the airfoil flow lab can be used to help students to get a better picture of the airflow around the Clark-Y airfoil model from the EFD airfoil experiment lab and can be used as benchmark data for the CFD airfoil flow simulation lab.

5.2 *ePIV/Flowcoach learning objectives*

The learning objectives of ePIV/Flowcoach labs are listed in Table 6. Two objectives were developed based on the lab concepts (Table 1) to cover the principles and applications of the PIV technique and to help students understand the fundamental fluid dynamics concepts better with the aid of flow visualisation. The lab reports, pre/post-test and end-of-the semester survey are used for assessment.

Table 6 ePIV/Flowcoach labs learning objectives and evaluation

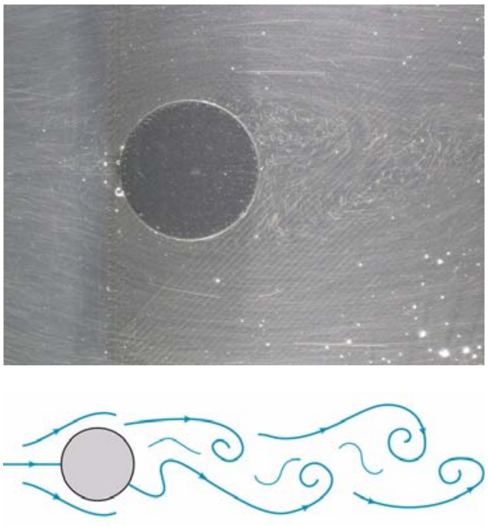
Objectives	*Assessment technique*	*Quantitative data on student performance (on a scale of 10)*										
		'02	*'03*	*'04*	*'05*	*'06*	*'07*	*'08*	*'09*	*'10*	*Avg*	*SD*
1 Provide students with 'hands-on' experience on the PIV flow visualisation and flow field measurement technique following the 'EFD process' to understand the principles and applications of the PIV technique.	Pre-test	n/a	n/a	n/a	n/a	n/a	n/a	6.8	3.8	3.7	*4.8*	*1.8*
	(Confidence)	n/a	n/a	n/a	n/a	n/a	n/a	(5.0)	(3.0)	(3.0)	*(3.7)*	*(1.2)*
	Post-test	n/a	n/a	n/a	n/a	n/a	n/a	8.5	7.5	5.9	*7.3*	*1.3*
	(Confidence)	n/a	n/a	n/a	n/a	n/a	n/a	(8.0)	(7.7)	(6.7)	*(7.3)*	*(0.7)*
	Score increase	n/a	n/a	n/a	n/a	n/a	n/a	1.7	3.7	2.2	*2.5*	*1.0*
2 Students will be able to understand fundamental fluid dynamics concepts better with the aid of flow visualisation.												

5.3 *Implementation*

The ePIV/Flowcoach labs are given during the EFD lab meeting hours. Typically two student groups attend the lab meetings and each group begins with either ePIV/Flowcoach lab or EFD lab then switches. The ePIV/Flowcoach labs also share the TM with the EFD labs. However, separate data reduction sheets or supplementary materials for the ePIV/Flowcoach labs as necessary. The hands-on experiment procedures for ePIV/Flowcoach labs follow the 'EFD Process' similar to EFD labs; however the UA step of the 'EFD Process' has not been implemented yet for the ePIV/Flowcoach labs.

Cylinder flow lab: the purpose of this lab is to visualise the flow around a circular cylinder model and to estimate the flow Reynolds number by comparing the flow streamline patterns from the visualisation with the published flow images tested at various flow conditions. Students also learn about the flow patterns around bluff bodies during this lab. For test setup, the ePIV/Flowcoach system is fitted with a circular cylinder model. By using the FLOWEX$^{\text{TM}}$, students first adjust the focus of camera and change camera control parameters such as brightness, exposure, and gain to achieve optimal flow streamlines visualisation. Once obtained the desired camera parameters, flow speed is adjusted over a range to observe how the flow streamlines pattern changes, especially at the wake region behind the cylinder. Students compare the streamlines from the ePIV/Flowcoach images with the provided sample images as guidelines and estimate the Reynolds number of the flow. Streamline images are captured for different Reynolds number cases ranging between approximately 2 and 90 according to the flow speed. Students report two ePIV/Flowcoach streamline images with specified the camera settings used for image capture, qualitative sketches of the streamlines, and the estimated Reynolds numbers for a low and high Reynolds numbers. Students are asked to explain the different flow patterns between the low and high Reynolds numbers, based on their ePIV/Flowcoach flow observations. A typical example of the Flowcoach streamline image is shown in Figure 9.

Figure 9 Streamlines visualisation around a cylinder model for the ePIV/Flowcoach cylinder flow lab (top) and a conceptual sketch of the streamlines from a textbook (bottom) (see online version for colours)



Step flow lab: the purpose of this lab is to measure the velocity field of the flow over a step-up model and determine the volume flow rate and cross-sectional average velocity of the flow. During this lab students learn about the fluid dynamics concepts such as the mass conservation law and the continuity equation. The PIV particle images from the ePIV/Flowcoach are processed for flow velocity vectors by using the FLOWEX™ software. For this, three PIV parameters can be adjusted including interrogation window size, shift size, and PIV pairs. The interrogation window size parameter sets the size of the PIV interrogation window in pixels. The shift size parameter determines the pixel distance that the software moves to start a new interrogation window. The PIV pairs parameter specifies how many pairs of images are used for PIV calculations. Results computed for each individual pair are averaged together, reducing precision error. Data reduction for ePIV includes the following steps: calculates the average velocity and flow rate for every *x*-value in the recorded data. Plot the calculated average velocities and flow rates versus *x*-position. Examples of the plots are shown in Figure 10. Students report plots of average velocity and flow rate versus *x*-position and answer to the questions about such as the effect of the cross-sectional area of the channel on the average velocity and the flow rate.

Figure 10 The ePIV image for a 'step-up' model for the ePIV/Flowcoach step flow lab (top) and example outcomes showing the flow rate and average velocity through the channel (bottom) (see online version for colours)

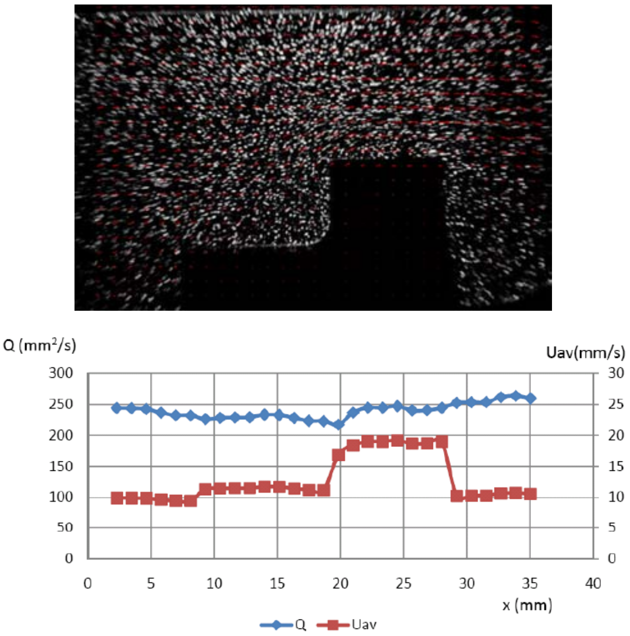
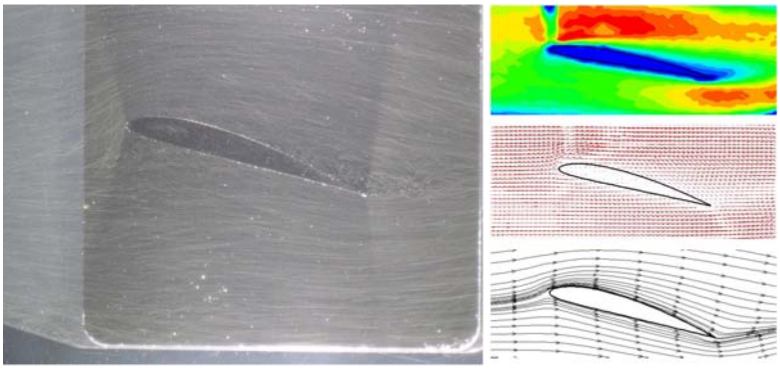


Figure 11 Streamlines visualisation around a Clark-Y airfoil model (left) and example data post-processing results (right) for the ePIV/Flowcoach airfoil flow lab (see online version for colours)



Airfoil flow lab: the purpose of this lab is to measure the velocity field around a Clark-Y airfoil model and post-process the data for velocity magnitude contours, velocity vector field, and flow streamlines plots. Students learn about the flow around a lifting body while conducting this lab. PIV images are captured and the flow velocity is analysed from the PIV images by using the ePIV/Flowcoach system and the FLOWEX^{TM} software. First, students calculate the flow Reynolds number by using the average inlet flow speed, airfoil model chord length, and the kinematic viscosity of water. Then, students generate plots of velocity magnitude contours, the velocity vector field, and streamlines around the airfoil for both 0º and 16º angles of attack by using commercial graphic software (e.g., Tecplot®). Examples of the plots are shown in Figure 11. Students report the flow Reynolds number and the plots and answer to the questions about such as the effect of angle of attack of the airfoil model on the flow pattern and separation.

6 Evaluation and assessment

The course and lab evaluation is based on student performance metrics in homework, quizzes, exams, lab reports and pre/post-tests along with an end-of-semester survey. The course and problem solving, CFD lab and EFD lab objectives were developed during the ISTUE project in collaboration with CEA, as shown in Tables 2 to 5. Recently ePIV/Flowcoach objectives were developed, again in collaboration CEA, as shown in Table 6. The pre/post-test and end-of-semester survey items were also developed in collaboration CEA. The student performance metrics and end-of-semester survey items are cross-references to the objectives, as shown in Tables 2 to 6. Data have been collected over the last nine years.

The pre/post-test consists of two forms (forms A and B) which are designed to be parallel. All test items are objectively-scoreable with a format of either multiple-choice or true-false or supply-type. Students are randomly assigned to take either form A or form B as a pre-test at the beginning of the semester. At the end of the semester, all students take a post-test, which include both sets of items from forms A and B. Thus, on the post-test, students respond to one set of items they had previously seen on the pre-test and an additional set of items that they had never seen before. In addition to responding to individual items, students are asked to rate their confidence in their response to each individual item. Confidence is rated on a four-point scale ranging from 'Just Guessing' (scored as 0) to 'Completely Confident' (scored as 3). On the CFD assessment, forms A and B each contains 11 items, ten of which are unique and one of which appears on both forms A and B. Thus, the CFD post-test includes 21 items. On the EFD assessment, forms A and B each contains 12 unique items. Thus, the EFD post-test includes 24 items. Finally, on the ePIV/Flowcoach assessment, forms A and B each contains six unique items. Thus, the ePIV post-test includes 12 items.

The end-of-semester survey items were developed for course general (8 items for 8 objectives), problem solving (27 items for 7 objectives), CFD labs (15 items for 8 objectives), and EFD labs (13 items for 5 objectives); total 62 items for 28 objectives. Note that one survey item was used for both CFD and EFD labs. Note also that two items for EFD labs are related to ePIV/Flowcoach labs. Students responded to survey items by using a six-point Likert type scale ranging from 'Strongly agree' (scored as 6) to 'Strongly disagree' (scored as 1). Respondents with insufficient information or who do not want to respond can choose a 'No opinion' respond.

Table 7 provides a summary of the evaluation. Presented in the summary are the time-average mean and standard deviations (SD) for the student performance metrics and end-of-semester survey items. It is noted that all of the assessment results were rescaled by using a ten-point scale for direct comparisons between different assessment techniques. The resulting scores can be interpreted to mean the number of items correct out of ten, as stepped up or stepped down depending on the total number of actual items on the assessment.

Table 7 Evaluation summary

Learning goal	*Assessment technique*	*Assessment period*[†] *(years)*	*Class-average* student performance*	
			Mean average (on a scale of 10)	*Mean standard deviation (% mean)*
Course general	Survey	6	7.8	7.1
Problem solving	Survey	9	8.2	3.1
	Homework	8	9.4	4.2
	Quiz	4	7.5	8.5
	Exam	9	8.3	4.9
		Average:	8.2	
CFD labs	Survey	9	8.2	3.6
	Lab report	6	9.3	1.5
	Pre-test (score)	6	5.2[§]	6.8
	(Confidence)		3.3[§]	
	Post-test (score)		7.1	7.7
	(Confidence)		7.3[§]	
	Pre/Post-test score increase		1.9[§]	40.5
		Average:	8.2	
EFD labs	Survey[‡]	9	7.9	4.4
	Lab report[‡]	6	8.9	3.2
	Pre-test (score)	6	5.4[§]	7.2
	(Confidence)		4.0[§]	
	Post-test (score)		7.5	6.0
	(Confidence)		7.0[§]	
	Pre/post-test score increase		2.1[§]	33.5
ePIV/ Flowcoach labs	Pre-test (score)	3	4.8[§]	37.4
	(Confidence)		3.7[§]	
	Post-test (score)		7.3	18.0
	(Confidence)		7.3[§]	
	Pre/Post-test score increase		2.5[§]	40.4
		Average:	7.9	

Notes: *Average number of students = 89 since year 2002.
†The actual assessment period may differ for each leaning goal items. Refer to Tables 2 – 5 for detail.
‡Combined assessment with the ePIV/Flowcoach labs.
§Not included in the average.
¶Number of students = 27.

Table 7 Evaluation summary (continued)

Learning goal	*Assessment technique*	*Assessment period*[†] *(years)*	*Class-average* student performance*	
			Mean average (on a scale of 10)	*Mean standard deviation (% mean)*
(Flowcoach only[¶])	Pre-test (score)	1	3.8[§]	
	(Confidence)		3.3[§]	
	Post-test (score)		6.4[§]	
	(Confidence)		6.7[§]	
	Pre/post-test score increase		2.6[§]	
	Course average:		8.1	
	Average pre-/post-test score increase:		2.2	

Notes: *Average number of students = 89 since year 2002.
†The actual assessment period may differ for each leaning goal items. Refer to Tables 2 to 5 for detail.
‡Combined assessment with the ePIV/Flowcoach labs.
§Not included in the average.
¶Number of students = 27.

Students performed better on homework and exams than quizzes with average grades 9.4, 8.3 and 7.5, respectively, which is not surprising since quizzes are unscheduled. The survey average was 7.8 for the general course and 8.2 for the problem solving. The SD is largest for quizzes and smallest for the problem solving, at 8.5% and 3.1% of the mean, respectively. The course general average is 7.8, the problem solving average is 8.4 and the overall average is 8.2.

Student performance was good on their CFD and EFD lab reports with average grade 9.3 and 8.9. The SD is small at 1.5% and 3.2% of mean, respectively, suggesting that all students performed consistently well. For CFD, the average pre-test grade is 5.2 with confidence 3.3, whereas the average post-test grade is 7.1 with confidence 7.3 which represents a post-test grade increase of 1.9 points, on average, transposed to the 10 point scale. For EFD, the average pre-test grade is 5.4 with confidence 4, whereas the average post-test grade is 7.5 with confidence 7 which represents a post-test grade increase of 2.1. The SD for the pre/post-tests is fairly large at 7% of the mean. For ePIV/Flowcoach, the average pre-test grade is 4.8 with confidence 3.7, whereas the average post-test grade is 7.3 with confidence 7.3 which represents a post-test grade increase of 2.5. The SD is large. For Flowcoach only, the average pre-test grade is 3.8 with confidence 3.3, whereas the average post-test grade is 6.4 with confidence 6.7 which represents a post-test grade increase of 2.6. The overall averages for the CFD and EFD labs are 8.2 and 7.9, which is similar overall general course and problem solving average.

In addition to objective evaluations, students were also given an opportunity to respond to open-ended survey items elaborating on their evaluations of the EFD and CFD labs and the hands-on component of the labs during the ISTUE projects. Student comments on the survey questions, for example, "Evaluate the hands-on aspects of this course …" or "What were the best features of the EFD/CFD lab and what worked especially well for you?", were grouped into a few categories and summarised in Stern et al. (2004a) for EFD labs and in Stern et al. (2004b) for CFD labs. In general students were more positive on the CFD labs appreciating the value of visualisation of CFD results and the ease of use of the CFD educational interface. At the same time students also suggested a number of improvements on the labs, for example, requesting more instructions on CFD modelling or on using the educational interface including manual mesh generation. For EFD labs, students commented that the hands-on aspect of the labs helped them learn, but many of the students commented that they needed more opportunity to learn or to be more involved in the test design and setup.

For ePIV/Flowcoach labs, students were asked to address their comments and suggestions on the labs at the conclusion part of lab reports during the time span 2008 to 2010. Students were mostly positive on the ePIV/Flowcoach labs. They felt that the labs were enjoyable and useful to understand fluids dynamics better, especially from the flow visualisation aspect of the ePIV and Flowcoach systems. However, students also suggested that the labs could be more comprehensive than the current lab implementations. It was remarked that most of the students, either positive or negative, wanted more hands-on experience with the labs.

Just as with previous studies of EFD and CFD conducted by Stern et al. (2006), pre-tests and post-tests were used to investigate students' ePIV and ePIV/Flowcoach outcomes. Tables 8 and 9 present more details about students' learning of the content. Table 8 reports the ePIV pre-test mean scores, mean 'Same Form' post-test composite scores and mean 'Parallel Form' post-test composite scores for students randomly assigned to take form A or form B as the pre-test. Although form A pre-test mean scores were slightly higher than form B pre-test mean scores (indicating form B was slightly more difficult), the similarity in mean scores suggests that differences in form difficulty were not substantial. Gain scores from pre- to post-test were highly significant. Pre-test mean scores represented roughly 45% and 30% of the maximum possible points respectively for forms A and B, whereas post-test mean scores (across both forms) constituted approximately 74% of the maximum possible points (six items). Thus, both groups of students demonstrated both practically and statistically significant growth in their mastery of course content during the fall semester, 2009. It should be noted that despite robust evidence of student growth, student scores on the pre-test indicate that incoming students were able to get a fair number of items correct prior to instruction.

Table 8 ePIV pre- and post-test mean composite scores by form assignment for 2009

Pre-test form	*N*	*Pre-test mean (SD)*	*Same form post-test mean (SD)*	*Parallel form post-test mean (SD)*
Form A	49	2.67	4.82*	4.26*
		(1.36)	(0.95)	(0.91)
Form B	51	1.88	3.94*	4.86*
		(1.27)	(0.99)	(0.96)

Note: *Indicates improvement is significant from pre- to post-test at the $p < .0001$ level.

Table 9 Combined ePIV and Flowcoach pre- and post-test mean composite scores by form assignment

Pre-test form	*N*	*Pre-test mean (SD)*	*Same form post-test mean (SD)*	*Parallel form post-test mean (SD)*
Form A	46	2.15	3.33*	3.65*
		(1.17)	(1.38)	(1.37)
Form B	47	2.26	3.74*	3.43*
		(1.29)	(1.37)	(1.26)

Note: *Indicates improvement is significant from pre- to post-test at the $p < .0001$ level.

Table 9 presents the similar data from fall 2010 but combines ePIV with Flowcoach outcomes. Just like Table 8, it reports the ePIV/Flowcoach 'Same Form' post-test composite score means and 'Parallel Form' post-test composite score means for students randomly assigned to take form A or form B as the pre-test. Pre-test mean scores represented roughly 36% and 38% of the maximum possible points, respectively for forms A and B, whereas post-test mean scores (across both forms) constituted approximately 55% and 62% of the maximum possible points. The researchers also investigated the test items with regard to discrimination, difficulty and sensitivity. Some of the test items were better at differentiating what students learned. The pre- and post-tests could no doubt have been improved with the addition of more high quality test items. In other words, the full scope of student learning might have been even more clearly demonstrated with better developed and more numerous items addressing the content. Such work is in process for future studies. Nevertheless, the current pre- and post-test data adequately demonstrate that students, aided by ePIV as well as Flowcoach, achieved practically and statistically significant growth in their mastery of course content during the fall semesters of both years.

7 Conclusions

The use of hands-on integrated CFD educational interface and EFD/ePIV/Flowcoach labs for an introductory fluid mechanics course is shown to be an effective means of introducing/training students in modern experimental methods and simulation technology while simultaneously increasing their understanding of fluid physics and class-room lectures based on evaluation over the last nine years. The development of the EFD labs would not have been possible without the continued support of the University of Iowa including the IIHR shop and staff along with the additional support during the ISTUE project. The development of the CFD labs was an outcome of the ISTUE project with continued support from the University of Iowa including the IIHR staff and FLUENT/ANSYS. It should also be mentioned that nine quarter-time teaching assistants are required for the class (three each for classroom lecture and EFD and CFD labs).

This research built on previous investigations (Stern et al., 2006; 2004b) to document students' outcomes on pre- and post-tests specific to ePIV/Flowcoach, demonstrating that students achieved statistically and practically significant growth in knowledge. Students' outcomes provided evidence that the ePIV/Flowcoach systems were effective in assisting students' understanding of the principles of PIV techniques and relevant fluid dynamics theories. Students' scores on lab reports showed evidence for acquisition of skill and knowledge related to the overall lab implementation goals. Students' growth between pre- and post-tests was substantial both for knowledge as measured and for their confidence ratings of that knowledge. Survey results demonstrated that as a result of the ePIV/Flowcoach labs, students could conduct experiments and analyse the ePIV/Flowcoach results to gain increased understanding of fluid physics.

Sustaining and further developing the hands-on integrated CFD educational interface and EFD/ePIV/Flowcoach labs is a major issue. Clearly, significant institutional commitment is required especially in support of the EFD labs and teaching assistants. For the EFD labs laser Doppler and hot-wire velocimetry are planned for the pipe and airfoil experiments, respectively, to replace the current pitot probe measurement systems. For the CFD labs, the most important issue is the continued development and use of the CFD educational interface since the end of the ISTUE project. A post ISTUE project workshop was held on July 14, 2005 at IIHR, supported by NSF supplemental funding, with over 30 attendees of whom 18 were external to the ISTUE project and representing 14 different universities and the departments of bio, marine, mechanical, nuclear, food, materials science and chemical, atmospheric sciences, and civil engineering. There was widespread interest in the workshop, although limited funding precluded more attendees. The primary purpose of the workshop was to disseminate the CFD educational interface and conduct an informal assessment of the merits of the interface and the simulations developed to date. Specific objectives included:

1. evaluation of the interface by peer faculty
2. identifying needed enhancements and additional simulations
3. determining applicability by peer faculty.

The workshop agenda covered demonstration of the CFD educational interface along with its previous implementation and evaluation, followed by visiting faculty presentations and discussion of applicability to match their teaching needs. The independent evaluation conducted by the CEA indicated that faculties found the workshop valuable and verified their interests in implementing and if necessary further developing and/or adapting the CFD educational for their respective courses and laboratories. An outcome from the workshop was an NSF National Dissemination proposal, which unfortunately was not funded since CFD was considered one example of the wider field of computational science; thus, a broader scope was recommended.

Another development was that FLUENT is part of ANSYS and Flowlab is no longer generally available, but to be replaced by the current ANSYS Workbench environment. Some ISTUE faculties have already transitioned to the ANSYS Workbench, but a general purpose CFD educational interface is not yet available.

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