Development of *Hands-On* Student Experience with Modern Facilities, Measurement Systems, and Uncertainty Analysis in Undergraduate Fluids Engineering Laboratories

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Abstract

Development described of *hands-on* student experience with modern facilities, measurement systems, and uncertainty analysis in undergraduate fluids engineering laboratories. Classroom and pre-lab lectures and laboratories teach students experimental fluid dynamics (EFD) methodology and uncertainty analysis (UA) procedures 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 computational fluid dynamics (CFD) and/or analytical fluid dynamics (AFD) results. Students 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. Students implement EFD UA for practical engineering experiments. Students analyze and relate EFD results to fluid physics and classroom lectures, including teamwork and presentation of results in written and graphical form. Implementation described based on results for an introductory level fluid mechanics course, which includes complementary CFD laboratories for the same geometries and conditions. The laboratories constitute 1 credit hour of a four credit hour 1 semester course and include tabletop kinematic viscosity experiment focusing on UA procedures and pipe and airfoil experiments focusing on complementary EFD and CFD. The evaluation and research plan (created in collaboration with a third party program evaluation center at the University of Iowa) is described, which focuses on exact descriptions of the implementations, especially as experienced by the students, including preliminary data on immediate student outcomes as documented for Fall 2003. The project is part of a three-year National Science Foundation sponsored Course, Curriculum and Laboratory Improvement - Educational Materials Development project with faculty partners from colleges of engineering at

Iowa, Iowa State, Cornell and Howard universities along with industrial (commercial CFD) partner FLUENT Inc., which mainly focuses on the development of the educational interface for teaching CFD. Also discussed are conclusions and future work.

Introduction

Engineering experimental fluid dynamics (EFD) testing is undergoing change from routine tests for global variables to detailed tests for local variables for model development and computational fluid dynamics (CFD) validation, as design methodology changes from model testing and analytical fluid dynamics (AFD) to simulation based design. Detailed testing requires use of modern facilities with advanced measurement systems (MS) following standard procedures and uncertainty analysis (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[1] and code certification[2] and ultimately credibility of simulation technology. Also, routine test data is more likely used "in-house" whereas detailed test data is more likely utilized internationally, which puts increased emphasis on standardization of procedures. Detailed testing offers new opportunities, as amount and complexity of testing is increased.

EFD is included in the undergraduate engineering curriculum both in introductory and advanced fluid dynamics and/or related courses such as thermodynamics, heat transfer, hydraulics, aerodynamics, chemical and bioengineering, etc. Traditionally, at the introductory level various experiments are used primarily to highlight fundamental principles, whereas at the advanced level more emphasis is placed on experimental methodology and procedures. Recent developments follow aforementioned engineering EFD testing trends by focusing on use of modern facilities[3, 4], MS[5, 6], UA[7, 8], and complementary CFD[9, 10]. In parallel, innovative and computer-assisted learning has influenced EFD laboratories through studio model[11] and *hands-on*[12] learning methods and remote[13, 14] and virtual[15, 16] laboratories.

The authors' institute has a long tradition of educational fluids engineering laboratory development beginning in 1939 with very significant contributions ca. 1950[17]. The present initiative builds on this tradition through development, implementation and evaluation of *hands-on* student learning experience with modern facilities, measurement systems, and uncertainty analysis. The initiative is part of a larger project[18] on integration of simulation technology into undergraduate engineering courses and laboratories through development of teaching modules (TM) for complementary CFD, EFD, and UA supported by National Science Foundation 3-year award. 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 development TMs, effective implementation, evaluation, dissemination, and pedagogy of simulation technology utilizing web-based techniques. Evaluation plan includes collaboration faculty from Iowa, College of Education, Department of Psychological and Quantitative Foundation and Center for Evaluation and Assessment. The present paper specifically focuses on the EFD and UA laboratory developments at Iowa. A companion paper at this conference describes most recent CFD laboratory developments[19].

Design of *Hands-On* Undergraduate Fluids Laboratories

The fluids laboratory at Iowa provides various facilities and MS for use in both introductory and advanced Mechanical and Civil & Environmental Engineering courses, especially the introductory level fluid dynamics course, which is a 4-semester hour junior level course required in both Departments and also frequently elected by Biomedical Engineering students. Traditionally, course used 4-lectures per week for AFD with a few additional EFD labs for purpose of highlighting fundamental principles. Tabletop buoyancy and stability and jet momentum and hydraulic flume sluice-gate/hydraulic jump labs conducted. Students often complained course overloaded even for 4-semester hours.

Original concept for present developments was tested in late 1980's and early 1990's through design and construction of modern research quality teaching wind tunnel, airfoil and circular cylinder models, modern surface pressure MS with workstation data acquisition and complementary "student-run" potential flow panel code solutions for comparison with EFD data. Test successful but also indicated that for full implementation restructuring of course and labs required and no question but that CFD software should be used, which was actually original goal but not realizable at that time. Also important that standard EFD UA procedures used in all the experiments, which was, in fact, required in upgrading the EFD tests for benchmark quality data?

During mid 1990's to 1999, course restructured for 3-semester hour AFD (3 lectures per week) and 1-semester hour (1 laboratory meeting per week) complementary EFD, CFD, and UA laboratories. EFD laboratories upgraded for present purposes and to include UA and achieve benchmark quality data, including tabletop viscosity, pipe flow stand, and wind tunnel airfoil flow experiments. Complementary CFD laboratories were developed using the commercial CFD software FLUENT. The course was also reorganized for web based teaching and distribution of materials http://css.engineering.uiowa.edu/~fluids/.

From 1999 to 2002, refinements made and overall approach used as *proof of concept* for initiation of present larger project, as described previously. First year evaluation confirmed implementation successful, but at same time indicated direction for improvements. Student anonymous responses suggest students agree EFD, CFD, and UA labs were helpful to their learning fluid mechanics and important *tools* that they may need as professional engineers; however, they would like that learning experience to be as *hands-on* as possible.

During 2003, additional improvements made for *hands-on* EFD laboratories, as described in present paper, including overall concept EFD laboratories. Here, *hands-on* defined as the use of EFD, CFD, and UA engineering tools in meaningful learning experience, which mirrors as much as possible *real-life* engineering practice.

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

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

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

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

CFD/UA Labs
1. Provide students with *hands-on* experience with CFD methodology (modeling and numerical methods) and procedures through step-by-step approach following CFD process: geometry, physics, mesh, solve, reports, and post processing.
2.Students will be able to apply CFD process through use of educational interface for commercial industrial software to analyze practical engineering problems.
3.Students will be able to conduct numerical uncertainty analysis through iterative and grid convergence studies.
4.Students will be able to validate their computational results with EFD data from their complementary experimental laboratories.
5.Students will be able to analyze and relate CFD results to fluid physics and classroom lectures, including teamwork and presentation of results in written and graphical form.

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

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

Lecture	**Other Docs**	**Lab 1: Viscosity**	**Lab 2: Pipe Flow**	**Lab 3: Airfoil**
EFD lecture	EFD UA Report Lab Report Instructions	Pre lab1 questions Lab1 lecture EFD 1 Lab1_UA Instructions_UA	Pre lab2 Questions Lab2 lecture EFD 2 Lab2_UA: Smooth Rough Instructions_UA	LAB3 lecture EFD 3 Benchmark Data Data Reduction Sheet Instructions_UA Combined EFD3/CFD2 report instructions
CFD Lecture	CFD lab report instructions	None	CFD Prelab1 CFD Prelab1 lecture CFD Prelab 1 questions CFD Lab 1	CFD PreLab2 CFD PreLab2 Lecture CFD Prelab2 questions CFD Lab2

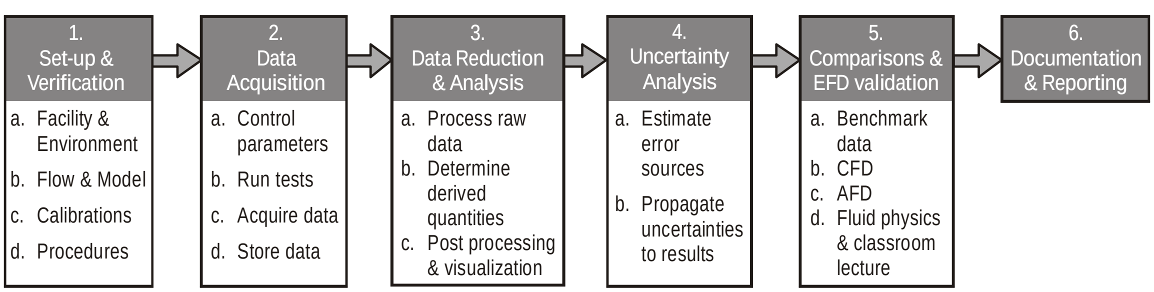

Fig. 1 The flow chart for *hands-on* EFD and UA labs.

Class web site provides EFD lab materials**.** The EFD lecture provides an overview of definition, purpose, and philosophy of EFD, types of measurements and instrumentation, measurement systems, uncertainty analysis, EFD process, and course laboratories. Lab report instructions guide students to write lab reports and can be used by teaching assistants to grade the reports easily. Different sections of lab report instructions are cross referenced to the Lab goals (Table 1), so the students' performances in the lab report can be used to provide evidence of students' skill and knowledge acquisition related to the lab goals. Prelabs used to familiarize students with specific purpose, test design, MS and procedures, UA, and data analysis and discussion for each EFD lab. Excel spreadsheets used to facilitate the UA. A companion paper at this conference describes CFD lab materials[19].

Viscosity Experiment The objectives of this experiment are to determine the kinematic viscosity of a fluid, the uncertainty of the measurement, and to compare the measured result with the manufacturer's value. The simple tabletop experimental facility shown in Fig. 2 demonstrates the effects of viscosity by comparing the fall times of different spheres in a long cylinder filled with glycerine. The data reduction equation for determining the viscosity is determined from the equilibrium of forces acting on the spheres with drag force provided by Stokes law. Teflon and steel spheres of different diameters used for the experiment. The required measurements are: ambient temperature, sphere diameter, and the time it takes for the spheres to fall between two markers at a fixed distance apart. Simple conventional tools such as tapes, micrometers, and stopwatches are used to conduct the experiment. The UA includes estimation of elemental sources of errors for all measured variables and 10 repeated tests to provide for the estimation of precision limits. Students report the glycerine density, kinematic viscosity and their uncertainty intervals as well as the comparison of their data with manufacturer's specifications. While most steps of the EFD process addressed, the viscosity experiment emphasizes UA.

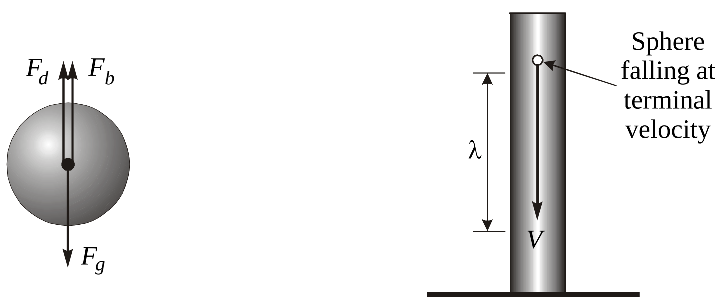

Fig. 2 Viscosity experiment

Pipe Flow Experiment The objectives of this experiment are to measure friction factor and velocity distribution in rough and smooth pipes and compare the results with benchmark data. The experiment conducted in a closed circuit pipe network of different roughness shown in Fig. 3. Experiment conducted in turbulent regime. The data reduction equation for determination of the friction factor based on a form of Darcy Weisbach equation with the geometry of the pipe and pressure measurements along the pipe at specified locations as the experimental inputs. The data reduction for the velocity measurements based on the Bernoulli equation applied to Pitot tube measurements, with separate readings of the stagnation and static pressures. The above mentioned pressure measurements, can be done in two ways. First method is to read pressure with a simple manometer while the second one uses a pressure transducer controlled by a computer-based automated data acquisition system developed with LabView software. The students use the first method during the prelab for demonstration purpose and the second method for acquiring data during the labs.

Fig. 3 Pipe flow experiment

Measurements on the smooth and rough pipes taken in parallel using two automated data acquisition systems. The students can observe real time displays of the pressure drops in two equal diameter pipes of different roughness factors, and the pipe velocity profiles and make a comparison between the two. The obtained friction factor compared with Moody diagram and with textbook velocity distribution. A spreadsheet provided to help the students with the uncertainty analysis procedure, and to calculate the flow discharge by integrating the velocity profile. The automated data acquisition system considerably facilitates the repeated measurements needed for uncertainty analysis. Students report friction factors and velocity distribution profiles with the associated uncertainty intervals and discuss the agreement of their results after comparing with the benchmark data. All steps of the EFD process addressed in the pipe flow experiment.

Airfoil Flow Experiment The goals of the airfoil experiment is to measure the surface pressure distribution and lift coefficient for an airfoil at a specified *Re* and various angles of attack and compare the results with benchmark data. The experiments conducted for a Clark-Y airfoil mounted in a closed circuit open test section wind tunnel shown in Fig. 4. The airfoil is provided with 29 pressure taps located in an airfoil cross section. The measured pressures used to calculate the pressure and lift coefficients. Pressure and lift coefficients are normalized with the free-stream velocity. Integration of the measured pressure distribution over the airfoil's surface used to calculate the lift force. Bernoulli equation used to determine the free stream velocity measured with a Pitot tube. The lift force independently measured with a load cell. Lift coefficients calculated for Re = 143,000 and several angles of attack up to the stall angle.

Fig. 4 Airfoil flow experiment

Tunnel control and the measurements made with instruments controlled by a LabView-based data acquisition program. A resistance temperature detector and a Pitot tube are used to measure the air temperature and free-stream velocity, respectively. The lift force measured with a three-dimensional load cell that calibrated by the students as part of their experiment. Students install the airfoil before conducting their experiment. The students introduced to the programming principles with LabView. In particular, the students are not only accessing the front panel commands as for the pipe experiment, but they familiarized with the program block diagram. Use of icons instead of text in development of the block diagram facilitates a hands-on experience of the students with modern data acquisition software.

Each group of students collects data for one angle of attack. Repeated measurements made for the uncertainty analysis. Similar to the pipe experiment, the data acquired by the students are stored on the class website from where the students download them for analysis. Students report the pressure coefficient distribution over the airfoil cross-section, and calculate the lift force and lift coefficient based on the pressure distribution integration. The pressure coefficient distribution and lift coefficient compared with benchmark data published in the literature. The lift force obtained through integration compared with the lift force directly measured with the load cell. UA conducted using a provided spreadsheet that contains estimation for bias limits for all variables involved in the calculations. All steps of the EFD process addressed in the airfoil flow experiment.

Self-Evaluation As part of the overall evaluation process, a self-evaluation was performed based on analysis of the data from students' performance and comments from their EFD reports, college of engineering EASY survey, and Course Outcomes Assessments Administered by Center for Evaluation and Assessment data. Most students' performance was very good, cooperative, and eager to learn. Students appreciated the *hands-on* EFD and UA labs, including use of modern facilities and MS and like fact that they could relate results to *real-life* applications. The analysis also suggested several ways to improve implementation. Use of smaller lab groups and more workstations so that all students directly involved with experiment. Use lab time more effectively by eliminating prelabs in favor of more student time actually performing their own experiments. Improvements to EFD lecture and lab materials and instruction, especially UA needs better instruction and concise instructions and lab reports. TA's lab reports grading is too liberal and does not break the grades to different categories as required by the lab report instructions. Also planned are improvements to the experiments themselves for generality (e.g., pipe transitions and alternative external flow geometries), greater depth in certain steps of EFD process such as use of LabView and advanced laser based MS.

Evaluation

The evaluation design applies instructional techniques and software in the context of different curricula at the different sites[20]. The focus herein is on the evaluation for The University of Iowa; however, similar results obtained at another of the NSF project partner universities. The guiding evaluation questions addressed by this design are the same at each site:

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

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

1. Student responses to independent, anonymous survey items asking them to judge their own learning from the EFD as they experienced it[21].
2. Student responses to independent, anonymous survey items asking them to provide evaluations of all the separate implementation components and to comment on how to improve the efficiency and effectiveness of the implementation, especially *hands-on* components.

The survey items were developed separately for and collaboratively with two of the university sites. Students responded anonymously to the survey items during the last week without the instructor present. Two sites did not participate in data collection and will not be included in this report. Surveys for the two participating sites included some shared as well as some unique items. Complete versions of the surveys as administered are available as PDF files at the following Web site: http://www.iihr.uiowa.edu/~istue/. At the two participating sites, open-ended survey items requested respondent comments. Also, students responded to direct statements indicating their degree of agreement or disagreement (e.g., "This information in this course was presented effectively" or "As a result of my learning in the EFD labs, I am able to conduct experiments in modern facilities such as pipe stands and wind tunnels). Respondents were asked to agree or disagree on a six point Likert type scale ranging from "strongly agree" (scored as 6) to "strongly disagree" (scored as 1) scale. Respondents with insufficient information or who otherwise did not want to respond could choose a "no opinion" response.

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

Table 3 presents the percentage of students at the Site I implementation whose lab reports indicated that specific instructional goals had been achieved.

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

Goals	**Lab report Sections**	**Student performance**		
		Lab1	**Lab2**	**Lab3**
1. Provide students with "hands on" experience with EFD methodology and UA procedures through step-by-step approach following EFD process: setup facility, install model, setup equipment, setup data acquisition using LabView, perform calibrations, data analysis and reduction, UA, and comparison with CFD and/or AFD results.	Total	91.5%	94%	94.8%
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,	2,3	29/30	29/30	29/30

<table>
<tr><td>including pressure transducers, pitot probes, load cells, and computer data acquisition systems (LabView) and data reduction.</td><td></td><td></td><td></td><td></td></tr>
<tr><td>3. Students will be able to implement EFD UA for practical engineering experiments.</td><td>4</td><td>15/15</td><td>15/15</td><td>15/15</td></tr>
<tr><td>4. Students will be able to use EFD data for validation of CFD and Analytical Fluid Dynamics (AFD) results.</td><td rowspan="2">5,6</td><td rowspan="2">36/40</td><td rowspan="2">37.5/40</td><td rowspan="2">37/40</td></tr>
<tr><td>5. Students will be able to analyze and relate EFD results to fluid physics and classroom lectures, including teamwork and presentation of results in written and graphical form.</td></tr>
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Site I Survey Responses For purposes of this report, survey items were categorized into clusters addressing the following topics:

- General Learning Needs Met by the Course (23 items, for example: "My learning needs were well met in this course", "The information in this course was presented effectively"
- Hands-on aspects of the EFD Component (2 items: "The hands on aspects of the Experimental Fluid Dynamics Lab helped me learn valuable skills and knowledge", The hands-on aspects of the Experimental Fluid Dynamics Lab worked well for me"
- Skills and Knowledge Gained Using the EFD Component (10 items: "As a result of my learning in the EFD Lab, I am able to present results from EFD laboratories in written and graphical form," "As a result of my learning in the EFD Lab, I am able to relate EFD results to fluid physics and classroom lectures".

Table 4 lists the items included in each cluster score. All cluster scores were investigated to determine their reliability[22]. Table 4 presents the internal consistency reliability estimates of the three cluster scores as well as their simple Pearson product moment correlations with each other.

Table 4. Cluster score reliability estimates and product moment intercorrelations

	Learning Needs Overall	Hands-On EFD	Skills, Knowledge Gained EFD
Learning Needs Overall	.94[a] (54)		
Hands-On EFD	.51 (54)	.85[a] (54)	
Skills, knowledge Gained EFD	.62 (54)	.70 (54)	.96[a] (55)

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

As can be seen in Table 4, all cluster scores showed high reliability estimates and moderate correlations with each other, suggesting that they provided good measures of the named constructs, and that respondents were able to differentiate the three constructs from one another. For example, the R^2 for the simple correlation of the cluster score "Hands-On Aspects of EFD" with the cluster score "Learning Needs Met Overall" (R^2 = .51 squared = .26) suggested that only about 26% of the variance in students' responses to the items constituting one of these cluster scores can be explained by students' responses to the other cluster score.

Of greater interest for the evaluation of the *hands-on* EFD component are the averages and distributions of these constructs. In general, the more strongly the students agreed with these items (or disagreed with the reverse, negatively stated items) the more agreement that their overall learning needs were met, for the quality of the hands-on components, or for the knowledge and skills gained from their EFD experiences.

Table 5 presents the means and standard deviations for each of these three cluster scores. Cluster scale scores are the sum of all scale item responses divided by the number of items in that cluster. This transforms the cluster score from a summed score to the same 1-6 range as the individual item scales, i.e. 6 = "Strongly Agree", 1= "Strongly Disagree".

Table 5. Cluster score means and standard deviations

Scale	*N* Cases	*N* Items	Mean	SD	Minimum	Maximum
Learning Needs Overall	55	24	4.56	0.65	2.81	5.63
Hands-on EFD	55	2	4.21	1.13	1.00	6.00
Knowledge, Skills EFD	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 (M=4.56 out of a possible 6.0, SD=.65), also "mildly to moderately" agreed that their knowledge and skills improved as a result of the EFD lab (M=4.55, SD=.93), and also "mildly" agreed that the *hands-on* EFD helped them learn (M=4.21, SD=1.13). 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 learning experiences were effective for them.

Students were also given the opportunity to respond to open-ended survey items elaborating on their evaluations of the EFD labs and the hands-on components of the labs. In response to the stimulus: "Evaluate the hands-on aspects of this course…" 38 of 62 students provided comments. Two raters independently categorized comments into positive and negative or areas for improvement related to the EFD.

<u>Negative Comments or Suggestions for Improvement</u>: 22 comments. Many students complained that the workgroups were too large, that student didn't really get *hands-on* unless they were the group leader, that they needed more opportunity to learn from minor adjustments to variables and be more involved in the conceptual design and experiment's set up, that it was too robotic and that was too much watching and not enough doing and involvement.

Positive Comments: 16 responses. In addressing what had worked well for them, students commented that the "progression from manual data gathering to the calibration of instruments to automatically gathering data worked nicely," and that the *hands-on* aspects helped them learn. One respondent mentioned the wind tunnel in particular as good, and several mentioned that it was helpful to see results after studying the material, or to get the practice in how to run experiments. Several expressed that they like the hands-on aspects and/or learned well from them.

In response to the question: "What were the best features of the EFD lab and what worked especially well for you?" 45 students out of 62 wrote comments. Two raters independently categorized all comments into one or more of four categories.

Tangible and real world aspects: 30 comments. Students appreciated using the equipment and "…being able to see what measurements were taken and getting a feel for flow rates, velocity, and other such measures…". They expressed appreciate for being able to see first hand what was happening. They liked having the actual objects to work on and operate, indicating that this facilitated greater understanding.

Instruction and teaching: 3 comments. Three respondents singled out the TA's work and excellent organization and explanations.

Data acquisition and analysis: 5 comments. Respondents expressed appreciation for the data collection and analysis part of the EFD lab.

Unsolicited Negative Comments: 3 comments. Three students did not like the EFD lab and felt disconnected from the learning experience. As one expressed it: "We never really did anything in the EFD. We just showed up and watch the instructor tell some people what to do."

In response to the question, "What needs to be improved in the EFD lab to maximize its value to you?" 45 students out of 62 wrote comments. Two raters independently categorized all comments into one or more of three categories.

Increase access and individual use: 14 comments. Respondents in general wanted the lab groups to be smaller and to have more individual access and use of the lab equipment. Students wanted to be involved in the set up as well as in running the experiments. They complained that a lot of people just got to sit around or be off to the side.

Instruction and teaching: 29 comments. Respondents wanted to be more involved in the actual set up and better understand what was going on. For example, one said: "The TA's did most of the work and we watched, hit some buttons, or turned a dial". Another said, "Sometimes it was confusing, trying to understand what we were exactly doing….seems like we were just pushing buttons and turning valves for no reason". One suggested to "make the experiment a separate course." Students also provided specific suggestions for speeding up the wind tunnel or simply modeling the airfoil with CFD, since you couldn't actually see anything.

Miscellaneous suggestions: 5 comments. Several students called the EFD lab boring or made suggestions for deleting EFD 3. One student commented that the EFD lab was excellent as is and needed no improvements.

Evaluation Conclusions The evaluation results indicate that considerable progress has been made toward developing a beneficial *hands-on* experimental fluid dynamics lab at these two sites. Both sites could be improved by increased capacity for smaller groups or through more student access to the equipment. Some students complain that they didn't feel their time was well-spent and they thought that they did not get enough meaningful access.

One important characteristic to be explored in future data collections is the variability in student responses. Students varied greatly in their judgment of benefit from the EFD 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 EFD experience are different from students who are frustrated and do not seem to benefit from the EFD lab. It may be that the implementation can only be improved so much and that some students will continue to benefit while others do not.

Conclusions and Future Work

Project successful in developing, implementing and evaluating EFD and UA labs for *hands-on* student learning experience with modern facilities, measurement systems, and uncertainty analysis, including complementary CFD labs. Evaluation indicates areas of strength as well as strategies for improvements and more effective implementation. Future work will focus on the following. (1) Additional course Sections and workstations for smaller lab groups. (2) Use lab time more effectively with improved teaching (especially UA) and improved instructions for labs and lab reports. (3) Improved and additional experiments offering more options for complementary CFD labs and greater depth in various steps of the EFD process such as use of LabView and laser based MS.

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