A Laser-Based Flow Visualization System for Fluid Mechanics Instruction

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Abstract

An interactive turbulent water flow facility and laser-based flow visualization system are used to reinforce fundamental concepts in the instruction of fluid mechanics. For this pilot study, the laboratory instructional module was incorporated into a single topic within the curriculum of a graduate-level fluid mechanics course. The laboratory treatment was used in addition to a traditional lecture-based treatment of the topic. Assessment methods including a content knowledge test and attitude surveys were used to examine the impact of the module on student learning and interest in engineering. Results revealed that the instructional module had added value over the lecture for increasing students' content knowledge (+50%). In addition, the visualization module received a significantly higher rating on the attitude survey than the lecture method for level of enjoyment, learning of content, and the development of interest in engineering.

Introduction

One of the principal challenges of teaching fluid mechanics is the level of abstraction that comes with the subject. Students tend to be more familiar with, and have better intuition for, the behavior of solids. Fluids move in complex and beautiful patterns, but the flow is often difficult to see with the naked eye. Despite the fact that we spend our lives immersed in a fluid (air), many fundamental fluid behaviors remain unfamiliar to students due to the difficulty in observing them. For example, we tell students that air in the classroom is turbulent, yet their acceptance of this is more an act of faith than an act of learning. Some fluid flow phenomena are more readily visible in liquids than in gasses, but this is usually true only at a free surface (an interface between a liquid and a gas), where flow-induced deformations of the free surface reveal information about the flow. Away from the free surface, most flow phenomena (e.g. turbulence, flow around obstacles, boundary layers, etc.) remain essentially invisible. To counter the level of abstraction associated with difficulties in viewing fluid motion, we built an interactive flow facility with a laser-based visualization system that enables students to directly observe a wide range of flow phenomena. The present research effort is a pilot study of the impact of the facility on student learning and attitudes. Students were exposed to content on the topic of turbulence through a traditional lecture and discussion method and a demonstration of the laser-based visualization system. The two instructional methods were compared via a content test of the material, an attitude survey, and a class discussion of the experience.

Researchers have historically used a variety of methods to render visible the unseen patterns of fluid motion. In a celebrated nineteenth-century fluid mechanics experiment, Osborne Reynolds introduced a filament of dye into laminar and turbulent flows in glass pipes.[1] The dye filament enabled Reynolds to visualize the presence (or absence) of turbulence, leading to the development of the famous Reynolds number criterion for turbulent flow. Today, state-of-the-art flow visualization techniques commonly employ lasers to illuminate fluorescent dyes or particles introduced into the flow. The most common technique is planar laser-induced fluorescence (PLIF, see example in Figure 1), although this technique has generally been limited to research applications.[2,3,4] These research techniques are now being adapted and implemented as instructional tools for fluid mechanics at the University of Colorado.

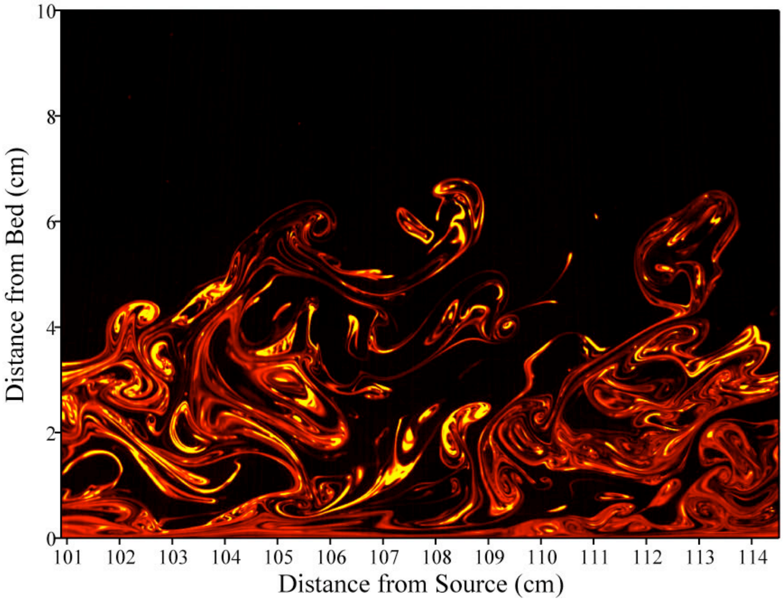

Figure 1: PLIF image of a contaminant plume developing in a turbulent boundary layer, with flow from left to right. The image is color-coded according to the concentration of the introduced contaminant (in this case, a fluorescent dye). The image shows the spatial distribution of the contaminant as well as information about the structure of the fluid turbulence.[3]

This adaptation is part of a broader context in which a variety of alternative instructional techniques are being incorporated into engineering education. These techniques are presented as an alternative to the traditional lecture method which has been frequently criticized by students and instructors for its focus on one-way communication and its insensitivity to a variety of learning styles.[5] Alternative instructional methods are typically classified as "active learning," and include lab demonstrations, cooperative learning, and problem-based learning. Researchers who have examined these methods have found extensive and credible evidence for their effectiveness.[6]

The turbulent flow facility built for the present study is shown in Figure 2. The facility consists of a 5 m long steel and glass test section, with fiberglass flow tanks attached to the upstream and downstream ends. Water is continuously pumped by a digitally controlled pump into the upstream tank, after which it flows through the test section and into the downstream tank. The glass sides and bottom of the test section provide easy optical access for the visualization system; the open top provides easy physical access to the flow. The flume is designed to maximize the student's ability to interact with, visualize, and quantify a wide variety of flow phenomena. The scale of the facility is small enough to permit easy and efficient operation while being large enough to permit the study of energetic flows common to natural systems. A variety of fluid flow phenomena can be created and studied in the proposed flume, including turbulent boundary layers, waves, wakes, hydraulic jumps, and dispersion of contaminants. One of the primary uses of the flume will be to study the transport and mixing of heat, chemicals, and other pollutants by turbulent flows in natural systems. A laser-based visualization system (described below) will enable the students to directly observe the physical processes that disperse contaminants and chemical signals in the environment. The study of these topics is essential to an understanding of the role that fluid mechanics plays in engineered systems as well as in biological systems and ecosystem dynamics.

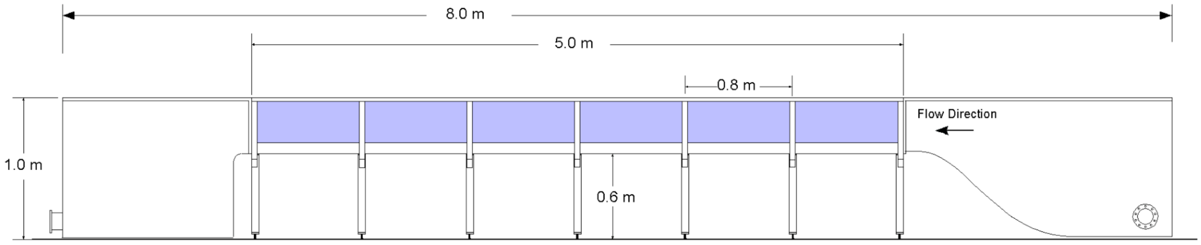

Figure 2: Elevation drawing of the turbulent flow facility.

A schematic of the PLIF laser-based flow visualization system is shown in Figure 3. The system consists of three main components: an air-cooled argon-ion laser, scanning optics to form the laser sheet, and a digital camera. The high-power lasers used in most PLIF systems present a significant safety hazard. To make our system safe for (supervised) undergraduate use, we use a low-power (150 mW), air-cooled, argon-ion laser. The optical system is designed so that a student could not inadvertently place their eyes in the path of the laser beam. Through careful choice of the laser wavelength and dye type, and by using a small study area, adequate fluorescence is still achieved with the low-power laser. The digital camera is a scientific monochrome device that can output image files directly to a computer in real-time. The camera is similar to the camera used in research PLIF applications, but with lower spatial and intensity-level resolutions (which greatly reduces the cost of the camera and the data storage requirements).

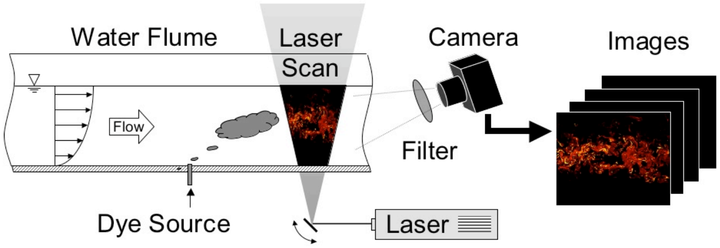

Figure 3: Schematic of the PLIF visualization system.

Students can quickly reposition and reorient the laser light sheet according to their needs. This encourages students to experiment with the system in order to gain several perspectives on the flow, and to gain "ownership" of the chosen experimental procedure.

Method

Nineteen students from a graduate level fluid mechanics course participated in a pilot study of the PLIF module. Students were first exposed to a lecture on turbulence followed one week later by a demonstration of the PLIF module. To quantitatively assess the impact of the module, a content knowledge test and an attitude survey were developed. The content knowledge test incorporated multiple-choice and discussion questions to cover the topic of turbulence. Content tests were scored by a third party using an answer key. On the attitude survey, students were asked to rate the lecture and the PLIF module on a five point Likert type scale according to the level of enjoyment, learning, and interest in engineering generated by each instructional technique. Content knowledge tests were administered two days before and four days after both the lecture and the lab demonstration. Attitude surveys were given along with the final content assessment.

In addition to the quantitative assessment, students participated in an in-class discussion where they were asked a series of open-ended questions about their experience in the pilot study. Students were questioned about the value and drawbacks of both the lecture and PLIF module. It was expected that this feedback would add depth and clarity to the quantitative results.

Results

Analysis of variance and t-test statistical procedures were used to test for significance changes in content test results and differences in student attitudes. Table 1 presents the results from the content knowledge test. Students made a small but significant 25% gain between the pre-lecture and post-lecture tests and a larger 50% gain between the post-lecture and post PLIF module tests. These results suggest the added value of the PLIF module for increasing content knowledge.

Table 1: Student Flow Visualization Test Scores Before and After Exposure to Different Instructional Methods

Comparison	Score 1	Score 2	Gain
Pre-lecture & Post Lecture	32%	40%	+25%*
Post-Lecture & Post PLIF Module	40%	60%	+50%*
			* p < .05

Table 2 presents the results from the student attitude survey. Student ratings of the lecture method averaged 3.63 out of 5 for enjoyment, learning of the content, and the development of interest in engineering. In contrast, student ratings of the PLIF module averaged 4.64 out of 5, a significantly higher rating. For the PLIF module, these results indicate a significant impact on student attitudes about engineering.

Table 2: Student Attitudes about Lecture and PLIF Demonstration Teaching Methods

Student Attitudes	Lecture	Lab Demonstration	Gain
Enjoyment	3.68	4.68	+27%*
Content Learning	3.89	4.67	+20%*
Interest in Engineering	3.33	4.56	+37%*
			* p < .05

Student responses to the open-ended, in-class questions generated several comments about the value of each teaching method. Students felt that the value of the lecture method was the opportunity to hear and interact with an “expert” on the subject. Students reported that lectures from experts are “hit or miss” depending on the “effectiveness” of the presentation. According to students, an effective presentation incorporates the following: clarity, organization, a measured pace, interaction, an outline of notes, and a variety of media for an appeal to different learning styles. The main drawback of the lecture method was its non-interactive nature.

Students felt the PLIF module was a good supplement to the lecture on turbulence bringing a “level of fun” to the class and providing an application of the concepts learned in lecture. Students felt the demonstration was particularly appropriate for learning about turbulence because of the abstract nature of the topic. Students cautioned that a bad demonstration method could be just as “painful” as a bad lecture. Instructors need to pay attention to the logistics of the lecture ensuring that facilities are appropriate for the class size and that all students have a chance to view the module.

Discussion

The PLIF module provided significant added value for increasing content knowledge and improving student attitudes about engineering. Student content test scores jumped 50% after the lab demonstration compared to only 25% following the lecture. In addition, students found the demonstration more enjoyable than the lecture, more beneficial for learning content, and more likely to increase interest in engineering. Students reported via the in-class discussion that they found the PLIF module particularly effective for teaching abstract concepts such as turbulence. These results add to the growing body of evidence supporting alternative instructional techniques as effective methods for teaching engineering.

Future research will expand upon the findings of this pilot study. This study will be repeated with a larger group of engineering undergraduates. In addition, the order of instructional techniques will be switched with the lab demonstration presented prior to the lecture.

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Biographies

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