## Implementation of Educational Particle Image Velocimetry Suites in Fluid Mechanics Laboratory Experiments

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### Abstract

The study of fluid mechanics is essential to many industrial and commercial applications. Examples include irrigation, sewer collection, water distribution, piping, heating, ventilation and air conditioning systems, aerodynamics, and power generation. Therefore, it is necessary that students have a good understanding of the concepts behind these and other applications. For this reason, the Civil and Mechanical Engineering programs at the College of Engineering at California State University-Los Angeles have two related courses in their curriculum: a theory course named CE/ME 303 Fluid Mechanics I and a corresponding laboratory course named CE/ME 313 Fluid Mechanics Laboratory I. Although the theoretical course has been developed to solve certain types of real-life problems involving fluids, unless one observes what they are, the knowledge is abstract. For this reason the Fluid Mechanics laboratory CE/ME 313, introduces the students through hands-on experiments, to several mechanisms seen in the theory course. Recently, the college of engineering through collaboration between its Center for Energy and Sustainability and Interactive Flow Studies Corporation acquired two educational interactive flow visualization systems, namely FLOWCOACH and ePIV. Flow visualization with these systems provides an excellent opportunity for visual appreciation of the complexity of flow phenomena. Some visualization experiments have been developed to enhance the learning experience and improve understanding on the following concepts: (i) streamlines, pathlines, timelines and streaklines; (ii) laminar and turbulent flow regimes on a flat plate; (iii) boundary layer development and its associated shear stresses, vorticity and the velocity field; (iii) separation in flows past an object; (iv) laminar flow over slender bodies, airfoils, or cylinders; and the development of vortices behind a moving object, among others. The paper presents some results of visualization experiments and their corresponding computational fluid dynamics (CFD) simulations, which may be used as a basis for the development of innovative teaching modules.

### Introduction

Now, more than ever, engineers are required to focus on sustainable designs that lead to more efficient systems with minimal resource consumption and reduced emissions. Required levels of efficiency can only be achieved with a deep understanding of the involved processes. Optimization of several engineering systems such as irrigation, sewer collection, water distribution, piping, heating, ventilation and air conditioning systems, aerodynamics and power generation can only be achieved with a deep understanding of fluid mechanics (FM). However, FM is often seen as one of the most difficult core subject encountered by students in engineering and physics. The problem stems from the necessity to visualize complex flow patterns and fluid behavior usually modeled by high level mathematics. In textbooks and classroom lectures fluid mechanics is treated as abstract, mathematical and conceptual, even though fluid mechanics is a visual subject. Particle Image Velocimetry (PIV) and Computational Fluid Dynamics (CFD) were adopted in a Fluid Mechanics course at California State University Los Angeles to help students better understand concepts such as streamlines, streaklines and pathlines and their implications in the commonly used Bernoulli's Equation.

Particle Image Velocimetry (PIV) is a unique laser based state of the art technology in fluid flow research that enables visual and quantitative analysis of the flow field; i.e., the fluid velocity as a function of both position and time. No other technology now or in the foreseeable future can do what PIV can. It is widely used in research and industry ranging from aircraft aerodynamics to improving heart implant devices. Some applications in which PIV has been used include (i) system design: where wind tunnel velocity experiments for testing aerodynamics of cars, trains, ships, aircraft and buildings have been done; (ii) general research: where velocity measurements in water flows for ship hull design, rotating machinery, pipe flows, channel flows, blood flow, hydrodynamics, spray research, combustion research, wave dynamics, coastal engineering and river hydrology have been implemented; and (iii) experimental verification of CFD models.

Computational Fluid Dynamics (CFD) is a sub-field in fluid mechanics which attempts to solve the detailed governing equations associated with the interaction between the fluid and the body (system), and its corresponding forces via numerical methods. Though the fluid flow can be described mathematically by a set of nonlinear partial differential equations; the resulting system of equations is usually very complex and are can seldom be solved analytically. This impediment is handled by means of computers and efficient algorithms that enable quantitative parametric solutions of the fluid flow in a system without the necessity of expensive experimental equipment.

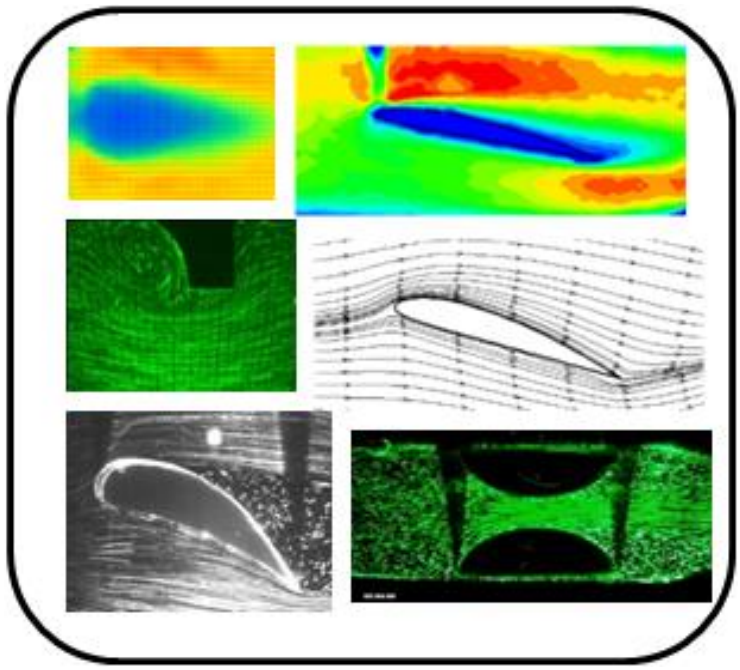
Although PIV is not a novel technology (Hopkinson, 1987; Wernet and Edwards, 1988; and Towers et al., 1991) its elevated cost has made its use for education purposes prohibitive. Recently, Interactive Flow Studies LLC (Interactive Flows Inc.) developed two educational instruments whose aim is to provide support in the quantitative and qualitative analysis of flow around objects, or flow through channels of different sizes and shapes. The instruments developed by Interactive Flows, named FlowCoach (shown in Figure 1) and ePIV are able to capture images of neutrally-buoyant particles, which reflect light and travel with the flow, allowing for qualitative analysis of the flow field. The data analysis is performed in a linux-based environment, denominated FlowEx. The FlowEx environment uses PIV data to compute parameters of the flow, such as velocity and pressure. FlowEx also provides the option for CFD analysis of flow using Gerris, an open-source framework to solve the governing equations (Popinet, 2010). The FlowEx interface allows for straight-forward CFD analysis of computer-aided-design (CAD) models to estimate velocity and pressure vector fields. These devices enable the comparison of experimental (PIV) and computational (CFD) data.

Herein, the potential use of FlowCoach to enhance teaching of fluid mechanics is investigated. In a laboratory experiment, students used FlowCoach to acquire velocity and pressure data for water flowing around a squared obstruction. The experimental data were then used to validate the corresponding CFD results obtained for the same conditions.

## Teaching Fluid Mechanics

The study of fluid mechanics has benefited from substantial contributions of various well-known scientists such as Archimedes, Leonardo da Vinci, Isaac Newton and Blaise Pascal. An important milestone in the advancement of fluid mechanics was the publication of "Hydrodynamica" in 1738 by Daniel Bernoulli, which lead to further investigations by past and current mathematicians, physicists and engineers. As fluid mechanics continues to evolve, a question remains. How can the body of knowledge that has been built over centuries be compiled and transferred to junior students over 4-quarter hours. Approaches that vary from regular lectures to more dynamic enthusiastic classes (Blanks, 1979) have been tried. Lately, the use of fluid visualization has been widely proposed and used, especially through the use of computational fluid dynamics (Curtis et al., 2004; Cimbala et al., 2004; Pines, 2004; Sert and Nakiboglu, 2007; and Hu et al., 2008).

(a)



(b)

**Figure 1.** FlowCoach by Interactive Flow Studies: (a) instrumentation; (b) sample of results.

The advantage of using CFD is that students are able to visualize velocity fields and track streamlines, streaklines and pathlines from the detail solution of the governing equations. However, in this case students are only dealing with mathematical models and often it is not easy to relate the theoretical model to the real phenomenon. Therefore, the use of PIV in conjunction with CFD is herein investigated as an approach to enhance teaching of most abstract concepts of fluid mechanics.

**Experimental Setup**

The FlowCoach equipment helps visualize fluid flow and can aid in the understanding of fluid mechanics concepts such as pathlines, streamlines, and streaklines. The experimental setup consists of a water/fluid reservoir, a flow model manufactured in acrylic, a camera, a set of neutrally-buoyant particles, and a PC containing the FlowEx environment (software) which will process the data. The neutrally-buoyant particles are mixed with the fluid, and travel with it as the fluid is pumped from the reservoir into the flow model section. As the fluid passes through the model section a camera captures the fluid motion, which is visible due to the reflecting characteristics of the particles. Once the images about the flow patterns have been captured by the camera, they are transferred to FlowEx for processing. FlowCoach uses light-emitting diodes (LED) as a light source whereas the source in the case of the ePIV is a laser. In either case, the flow patterns that are observed provide a true qualitative representation of the fluid flow, as it passes through section where the model is located. The idea behind this type of experiments is that students are able to relate the theory seen in the lectures to the actual visualization of the water flowing through an obstruction. Nevertheless, PIV is also able to provide quantitative results.

The motion of the particles is recorded by the camera and divided into a sequence of frames. The current camera records at a maximum speed of 30 frames per second, thus setting the maximum number of sequential frames at 30. It is important to note that the maximum flow rates and velocities that can be resolved depend on the frame rate capability of camera used. After the set of frames has been stored, FlowEx uses the frames to compute the velocity vector field for the flow at hand. The vector field is obtained by comparing a set of consecutive frames and determining the average distance that the particles have traveled. Once the distance has been determined, it is divided by the time interval between each frame, thus producing the velocity output (velocity = distance/time). Since this process is carried out between two consecutive frames, it is called a picture pair. It is important to note that, as more picture pairs are considered, the averaged results provide a better estimate of the actual velocity of the fluid. This technique is called particle image velocimetry (PIV) and produces the average instantaneous velocity of the fluid at a given location. The PIV-velocities provide quantitative data which can be analyzed and compared to the data produced by the CFD. A computer aided design (CAD) file is a computer representation of the flow model. The CAD file is integrated into the numerical analysis to solve the mathematical equations that describe the fluid motion. CFD will produce velocity and pressure vector fields at each node of domain under consideration.

The advantage of using FlowCoach is that it enables qualitative (visual) analysis without the need of any computer or data processing; it also allows for flow control. The disadvantages of using FlowCoach, being this an experimental system, are that at (1) high flow-rates (i.e., high velocities) the PIV analysis produces inaccurate results, (2) we are limited to using 30 frames/second (though the camera can be replaced for one with higher resolution), and (3) the analysis depends on the positioning of the camera which makes direct comparison between PIV and CFD more complicated. The advantage of using ePIV, on the other hand, is that the camera is fixed, thus the user does not need to adjust its position. However, a main disadvantage ePIV is the lack of a calibrated flow-rate control. Also, the analysis in both systems is limited to steady flows.

**Preliminary Tests**

Students were asked to validate analytical results using experimental data. The experimental test consists of flow visualization around a squared obstruction, and particle image velocimetry (PIV) analysis of the flow around such an object. The analytical test, on the other hand, consists of performing a computational fluid dynamics (CFD) study of the flow under same conditions of experimental setup. The validation is carried out using Bernoulli's principle to reinforce learning of fluid dynamics.

Bernoulli's principle, described by Equation (1), states that sum of kinetic and potential energy is constant along a streamline. The streamlines in the experiment can be observed qualitatively by tracking the particles flowing with the fluid (water). Figure 2 shows a 3-image sequence captured 1/30 s apart. In this sequence it is possible to notice the movement of particles, as highlighted in Figure 1. PIV uses the position at different times to develop the velocity field vectors (Figure 3), allowing for quantitative analysis of the flow.

$$\frac{V^2}{2g} + \frac{P}{\gamma} + Z = Constant \quad (1)$$

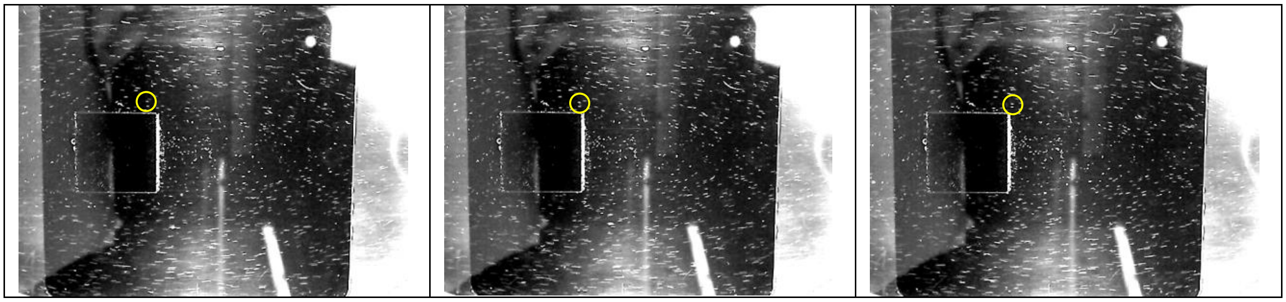


**Figure 2.** Sequence of images obtained by FlowCoach for PIV analysis (note: the yellow circle in the images depict the region where tracking two particles as they move around the obstruction is done).

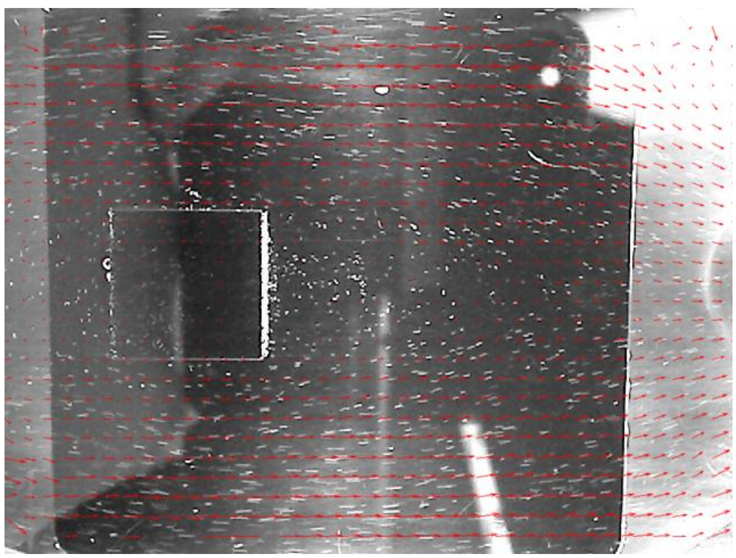


**Figure 3**. Velocity field obtained using FlowCoach particle image velocimetry (PIV)

CFD data is validated against the experimental data (PIV) by selecting two points on the CFD velocity vector field and by checking if the Bernoulli's constant in Equation (1) equals the one computed using the PIV. These two points are assumed to be along the same streamline, which is identified by students using the velocity field. The pressure differential between these two points is calculated using the tabulated velocity values. The reference points are then located on the PIV velocity vector field as seen in Figure 4. Assuming that the points have the same location with respect to that of the squared obstruction, the pressure difference between these two points is assumed to be the same as that between the points in the CFD results. Under such assumption, the Bernoulli constant was found for PIV data and can be compared to the Bernoulli constant for the CFD. Figure 5 shows a comparison in the values of Bernoulli's Constant obtained using CFD and PIV for different locations in the y-direction. As expected, there is a linear relationship between constant values and the location away from the body. Also, results show a very good agreement between PIV and CFD data with an overall average error of 5%.

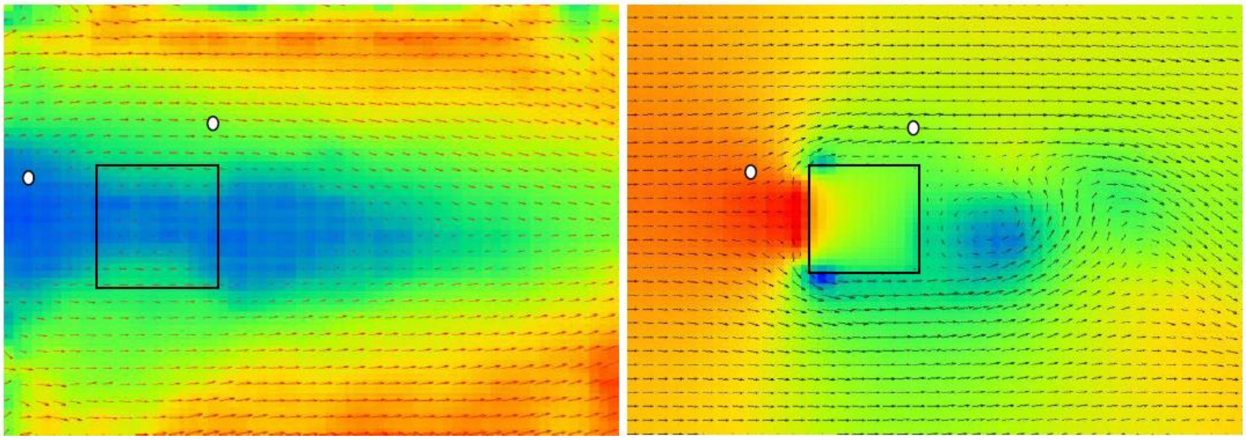


**Figure 4.** Velocity vector field from (a) experimental data, PIV and (b) computational data, CFD.

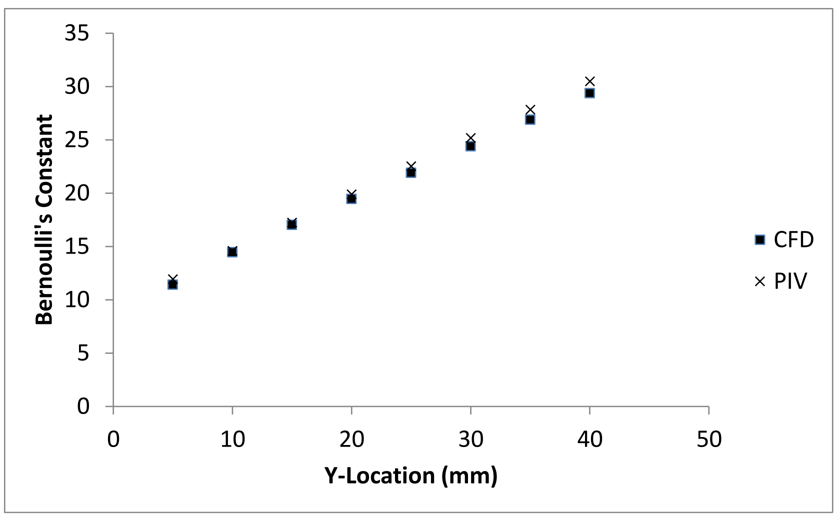



**Figure 5.** Values of Bernoulli's Constant as a function of location away from the body (x=15mm from leading edge)

## Future Directions

The results of this preliminary study indicate that CFD along with PIV visualization capabilities may have a positive impact on students learning of abstract concepts in fluid mechanics. Thus, the next steps that will be undertaken include the development of teaching modules and corresponding effective assessment/evaluation tools, and the results will be presented in the future.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