Educational Particle Image Velocimetry
Interactive Experiment Suites

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Interactive Flow Studies

Abstract: Laboratory experience is an essential component of teaching Fluid Mechanics. Hands-on teaching methods provide a lasting understanding of the fluid flow principles. Particle Image Velocimetry (PIV) has become a very powerful technique for studying fluid mechanics. Unfortunately very high price and safety concerns of using Class 4 lasers prevent this technology being used in the undergraduate and graduate laboratory teaching. Recently, however, a relatively inexpensive, and safe for classroom use ‘educational Particle Image Velocimetry’ (ePIV) system with web based interactive software was developed. This novel technology is an instrument that can be used in diverse educational settings because of its effectiveness as an education tool, high-tech appeal, compact size, low cost and safety. In this paper we introduce ePIV, describe its components in detail and provide examples of how it can be used to enhance undergraduate and graduate laboratory experience.

1. Introduction

Creativity is essential in generating scientific and technological breakthroughs. One way to develop and encourage creativity in students is to combine theory and practice in education. In this paper the focus will be on teaching of fluid mechanics. The laboratory experience has proved to be a crucial component of instruction in Fluid Mechanics. The hands-on opportunity provides a compelling and lasting perspective of the realities of fluid flow, aspects that are missing from books and computers. The Particle Image Velocimetry (PIV) has become a very powerful technique for studying fluid mechanics.

The setup is intended for educational use with the purpose of providing actual visualization and validation of the various flow phenomena in fluid mechanics studies. When studying a particular fluid mechanics theory - for example the concept of convective acceleration - flow in converging nozzle can be measured experimentally, and this can be correlated to the theory. In addition the PIV system can be used in senior design classes to visualize the actual flow in a prototype. It will provide a physical grasp of the theory, and a real appreciation of how the theory is applied in daily life situations. Correlations between the theory and actual flow visualization helps students and educators to fully understand the issues and benefits of fluid mechanics in a wide range of applications spanning from the fluid machinery to emerging applications, such as environmental, biological and micro-scale flows.

Design optimization is a common practice in industry. Students learning the design optimization process early in their career will benefit from this experience greatly. In fluid mechanics engineering a product development cycle starts with a design, and this initial design is optimized using Computational Fluid Dynamics (CFD). The purpose of the CFD is to minimize the number of tests that needs to be performed during the validation process of the design. This reduces the cost of development as tests are more expensive then the computational effort. The optimized
design is then tested. If the results do not agree with the CFD analysis, then the design process repeats itself until an optimized working design is achieved. The same design process can be taught to students using the ePIV system using an approach depicted in Figure 1.

![Figure 1. Fluids engineering design process](image)

Our motivation behind developing the ePIV system is to offer a PIV system that is safer, easier to use and significantly lower cost than the existing PIV systems. It is believed that such a system may be a great asset in high level education. The ePIV system addresses the shortcomings of existing PIV solutions and allows access to the highly visual PIV technology in education. In the following sections, details of the ePIV hardware as well as the software will be presented. Then class design of this technology, examples, and ABET outcome assessment will be discussed. Finally, discussion and concluding remarks will be presented.

2. **Particle Image Velocimetry**

PIV technique has been used extensively in research environments and has been available for more than two decades. A typical PIV system consists of a digital camera, a pulse laser such as a Class IV Nd-YAG laser, an optical arrangement such as a cylindrical lens to obtain a laser sheet, a synchronizer to synchronize the camera and pulses of the laser, and software to display and analyze the results. PIV is a measurement technique to capture flow velocity. Small “seed” particles are added into the fluid, and their movements are measured by comparing two images taken within a short time interval of the flow field using cross correlation. The major advantages of the PIV technique are:

a. Fluid mechanics is a highly visual subject and PIV takes full advantage of this fact. Multiple instantaneous whole flow field velocity images provide visual confirmation of flow patterns that is very useful in understanding flow phenomena.

b. It is nonintrusive unlike, for example, a hot wire anemometry. Introduction of carefully selected seed particles has practically no effect on the flow.

c. Large quantities of image pairs can be obtained in a relatively short period of time, and analyzed rapidly with a personal computer with immediate results and gratification.
The user must also be aware of the limitations of the PIV technique:

a. The velocity vectors are calculated using cross correlation of intensity distributions over small areas of the flow field. So the velocity field is a spatially averaged representation of the actual flow which directly affects the derived parameters such as vorticity.

b. 2D PIV does not account for the third component of the velocity field which can interfere with the 2D data.

c. The seeding particles may not always exactly follow the flow motion because of their potentially different density.

d. Another major drawback of a typical PIV system is that it is prohibitively expensive and uses a Class IV laser which is a safety hazard, especially in an educational setting. A Class IV laser can burn the skin and can cause permanent eye damage as a result of direct or reflected beam viewing. Class IV lasers are also a fire risk as they may also ignite combustible materials.

3. **Components of the ePIV system**

In this section, the ePIV hardware will be discussed followed by the software. Typical operation procedure will also be explained.

3.1. **ePIV hardware – Interactive Experiment**

The Interactive Experiment hardware can be seen in Figure 2.

![Figure 2. The ePIV system](image)

The interactive experiment system is portable and it consists of a rugged module, housing all the system components. The components include a PCB mounted digital camera, a laser, an optical lens for the laser light, a small variable speed water pump, a reservoir, and an interchangeable experiment module. All the components, except the flow model, are fixed in the housing without any need for further adjustments. The flow model, on the other hand, is designed to be modular so that it can be removed and replaced from the housing. The main purpose for such flexibility is to allow different flow models to be used with the system with minimal effort. The experiments will include many flow models of interest such as a venturi. Various experiment modules are provided with the system and more can be custom made or introduced by the educators. Water and seed particles are added by the user and replaced or refilled as needed. Seed particle selection takes into account the buoyancy and reflective index.
of the particles. Neutral buoyancy is important for seed particles to follow fluid motion, and a high reflective index is required to capture frames suitable for PIV analysis. The reservoir is connected to the flow model through a pump. The tubing can be disconnected without loss of water and spills. The clever system of tube connections allows instantaneous change of flow direction by the turn of a valve. This can create very interesting flow phenomena. The flow inlet and outlet to the experiment are connected to the pump by transparent flexible tubes. The pump was selected to provide sufficient pressure head to overcome the pressure drops in the system which includes flow through the flow model and laser cooling. The pump also had to be quiet with relatively low vibration, as the vibration can interfere with the operation of the camera. Transparent and flexible tubing helps the user remove any bubbles easily and quickly. Also, if there are bubbles, with proper settings of the camera parameters the bubbles can be made dark while still keeping the seed particles bright enough for PIV analysis. Reflective properties of the seed particles were chosen to ensure this. Flow chamber is positioned to minimize gravitational effects. The relative positions of the flow chamber, laser and camera are such that the camera resolution and laser intensity are fully utilized. The camera supports a range of parameters suitable for PIV as well as flow streamline visualizations. The camera conforms to standards so that it can be used from various hardware and operating systems including GNU/Linux. It has a reasonably high frame rate (30fps) and resolution (640x480). Some of the important criteria for the camera selection were reasonable frame rate, resolution and cost. The laser is a 15mW green continuous diode laser, and it is water cooled for continuous and reliable operation. The laser is completely enclosed and it is not visible to the user to ensure safety. Furthermore the safety switch turns the laser off automatically if the flow module is removed. Since the system is to be used by educators and students, the unit is specifically designed to be safe without any exposure of dangerous laser light to be seen by the operator with typical use. The light intensity is sufficient to illuminate the seed particles at the fastest frame rate of the camera. The laser is fixed on a dampening mount so that it is robust during transport and handling by the user. A valve enables the student to change the flow rate, which allows the student to study the effects varying the flow velocity. The output from the ePIV system is a USB 2 port for the data transfer to the computer.

A great deal of research went into the design. During development over the last two years many components were examined and a few of the promising ones were tested. In summary, the hardware is robust, very compact, self contained, safe, easy to operate, modular and very user friendly. It can work in a lab environment as well as in a class or office. It uses well supported and compatible hardware.

3.2. ePIV software - FLOWEX™

In addition to the system module, containing all the hardware, there is the associated software package, FLOWEX™, specifically designed and developed for an education environment. FLOWEX™ is a set of user friendly programs distributed as a bootable, self-contained CD, DVD, or USB stick without any special requirements of external software packages or libraries to be installed. The software is independent of the original operating system. FLOWEX™ software automatically transforms any Intel x86 compatible computer with suitable hardware including a USB 2 interface into a FLOWEX™ system. To start FLOWEX™ the user just boots the computer from the CD, DVD or the USB stick. It does not affect the original operating
system. The user computer does not depend on any additional software. Any type of computer with network access and a browser would work. Everything can be controlled through a web interface, primarily using a mouse. The software can be used directly on the host computer, or multiple computers can connect to it and share it through a network using typical web browsers. For example, a host computer may be designated and shared across a local network such as a local wired/wireless network. Students or multiple users can connect to it remotely using their notebooks or lab computers without needing to install any new software on their own computers. Access by multiple users encourages team work and team discussions and explorations. Operation through remote web access makes ePIV suitable for distant learning as well. FLOWEX™ is designed to be user friendly with instructions available for each step. It is interactive so that the user can visualize the flow field in the flow model and obtain the velocity results instantaneously. Using the velocity results, other fluid flow quantities can also be calculated. Some of those quantities include vorticity, strain rates, shear rate, streamline, contour plots and other relevant results. Users can download all raw and processed results, embed them in their papers, lab reports, or process them further offline since all formats are open and compatible formats that can be processed by a wide range of free as well as commercial software. The software includes the following features:

Camera control and image capture: Various parameters of the camera can be controlled by the user including brightness, exposure, gain, and number of frames to be captured. Figure 3 displays the camera control and preview interface. A preview of the video is displayed in the preview interface. For PIV analysis, camera parameters are typically set in a way to have seed particles as bright spot points in the image, while the background is as dark as possible. For streamlines visualization, exposure and brightness can be increased to form virtual streamlines. Once suitable frames are captured further analysis can be carried out.

![Figure 3. The FLOWEX™ software – camera control and preview section](image-url)
**Analysis and display**: The PIV module allows the user to control interrogation window size and shift parameters and sets the remaining parameters to suitable defaults based on the input images without overwhelming the user with up to dozens of parameters, which typical PIV software may contain. Shift size controls how many pixels are needed to move in each direction to initiate another interrogation. Flow is visualized by displaying velocity vectors obtained through PIV. Velocity vectors can be obtained separately or overlaid on top of the original image. The results are displayed in pseudo color to distinguish different velocities. From the velocity vectors other flow parameters such as vorticity or velocity gradients can be calculated. Raw data and results can be downloaded in various open formats (jpg, png, ps, eps, plain text) for offline processing or for inclusion in lab reports or papers. Results are provided in both pixel and millimeter units. Velocities are available in pixel per second and mm per second. Note that conversion between units can easily be achieved by knowing the time difference between consecutive frames (e.g. 1/30s for a 30fps mode) and by knowing the dimensions of the flow model and how many pixels it corresponds to (e.g. 1 pixel is 0.05 mm).

**Fluid mechanics theory**: the information contained in the software is highly interactive. The textbook style information allows the students to relate to the experiment by performing interactive flow experiments through the ePIV module. Various resources and discussions are available along with pointers to more information such as related papers and resources available on the Web.

**Assessment tool**: The instructor can assess students’ understanding of basic fluid flow theory, as well as experimental techniques, from their written report on the ePIV experiments. More information is given on the expected format of typical students’ report in the class design in Section 4. The instructor may also remotely access the ePIV system through the web based FLOWEX™ software during the lab session and monitor the students’ experiment.

**Print out or export results**: The results of the experiment can be disseminated by printing or electronically.

FLOWEX™ software offers compatibility on multiple fronts, and provides the users access to a broader range of additional software if they choose to use them. For example, the hardware and file formats used in FLOWEX™ software are compatible with GPIV, an open source and free PIV software available on various GNU/Linux distributions. FLOWEX™ software image format is compatible with GPIV and other PIV software so users can read it through those programs. Exported data formats are either plain text (ASCII), or open and common file formats such as postscript, png, and jpeg. ePIV hardware is compatible with Coriander, and other open source camera control software, which can be used to control the camera for real time streamline visualization and image/video capture.

**4. Class design using this technology**

In this section typical instructional sequence that the students would follow to complete an ePIV laboratory session will be outlined. The students begin by taking a class on fluid mechanics basics such as streamlines, flow separation and reattachment, mass flow and continuity, laminar flow, recirculation, etc. The laboratory class would then begin with an ePIV demonstration by
the instructor. The ePIV system will allow students to make experimental observations of the principles they just learned in the class, which aims to provide a deeper understanding of the fluid flow principles. The students can work in groups of three or four in a laboratory or classroom setting. They can run FLOWEX™ software without being connected to the internet. But if they connect FLOWEX™ to the internet, then multiple users can connect to FLOWEX™ remotely, as explained in Section 3.2. A diagram of an example remote access arrangement can be seen in Figure 4. The instructor can also remotely monitor or help the students while the students are running the ePIV system.

![Figure 4. Example remote access arrangement](image)

By looking at different geometries the student can discover the effect the boundary has on the flow phenomena. The flow models can be numerous. For example, flow separation could be effectively visualized and studied using circular, and half cylinders, and triangular, rectangular blocks, etc. The student can study the effect of various obstruction shapes on flow. Six flow models are supplied with the system as standard which can be seen in Figure 5.
Custom models are also available. Possible options include aerofoil or a cylinder as can be seen in Figure 6. These are made from acrylic where flow - full 360 degrees - around the obstruction can be studied. The wing angle can be changed.

The camera and PIV settings are interactively varied by the student, and the interactive nature of ePIV allows students to achieve good results in a short amount of time. The student uses visual validation to achieve good results. The results would not be considered good if the vector field clearly deviate from the coherent ones, or there are simply no vectors. ePIV system makes the selection of parameters easy enough so that most students can achieve high quality results in a relatively short amount of time, but probably not in their first attempt. Changing parameters and retrying is made extremely easy to motivate experimentation and learning from mistakes without getting frustrated. More information on PIV vector validation is given in a paper by Usera, and also explained in FLOWEX™ software as part of the operational instructions.

The student captures a series of images with the camera, and these images can be monitored. PIV analysis requires two consecutive frames so that the displaced particles can be cross correlated. Typical first and second frames can be seen in Figure 7. The second frame is similar to the first frame but with displaced particles. This displacement and the knowledge of the time between the two frames provide the velocity of the particles. Students select the parameters of the system such as window and shift size. The bigger the window size, the more stable the computed vector is, but it will average over more pixels, hence risk losing information on local flow. On the other hand a small window size gives more information on local variations but it has more noise.
At the end of the ePIV laboratory session the student can be asked to write a report with considerations summarized in Appendix A.

5. **Examples**

In this section we will walk through some examples. As a typical example the Gradual Step flow model insert was used. The most common mathematical method for flow visualization is the streamline pattern. The pattern, which several streamlines form, gives a very good description of the flow. In steady flow streamlines and streaklines are identical. Traditionally, a streakline can be produced experimentally by the continuous release of marked particles such as dye, smoke or bubbles\(^6\). In ePIV streaklines are visualized using solid particles which are illuminated by a laser by increasing the exposure of the camera. It is not possible to fully demonstrate the teaching effectiveness of seeing the videos and interacting with ePIV in a non-interactive medium, but FLOWEX\(^\text{TM}\) dynamically generates videos of the flow that clearly shows flow separation, rotational flow, unsteady flow and effect of sudden flow reversal. A snapshot from a video, which can be seen in Figure 8, may perhaps give a glimpse of what can be achieved.

![Figure 8. Flow streamlines](image)

FLOWEX can post process the data in the form of velocity vector plots. The velocity vector field is superimposed on the image as can be seen in Figure 9.
Figure 9. Gradual step flow model example

The experiment clearly shows that the flow accelerates as the width of the channel decreases. This is a demonstration of continuity. The incompressible continuity law states that:

\[ Q = \int u \, dA = \text{Constant} \]

Where \( Q \) is the flow rate, \( A \) is the cross sectional area and \( u \) is the velocity. The vector field can also be plotted as can be seen in Figure 10.

Figure 10. Vector field plot
Raw data can be exported for further analysis as can be seen in Table 2.

<table>
<thead>
<tr>
<th>mm/s</th>
<th>1.94</th>
<th>2.32</th>
<th>2.59</th>
<th>3.57</th>
<th>4.39</th>
<th>5.65</th>
<th>7.23</th>
<th>8.95</th>
<th>10.35</th>
<th>12.55</th>
<th>19.05</th>
<th>23.95</th>
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<tbody>
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<td>17.95</td>
<td>19.64</td>
<td>19.44</td>
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<td>15.15</td>
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<td>16.21</td>
<td>14.64</td>
<td>13.15</td>
<td>11.85</td>
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</table>

Table 2. Speed versus location matrix

The flow model is 30mm x 25mm and the number of (u, v) data points are specified by the student so the size of the table in Table 2 depends on the number of data points the student wants to analyze. The speed results can also be plotted in shaded format from the exported data which can be seen in Figure 11.

![Figure 11. ePIV instantaneous flow speed shaded plot](image)

The data obtained from the experiment can be used as boundary conditions for the CFD analysis. The CFD results can be validated with the experiment. The velocity vector field from the CFD can be seen in Figure 12.
It is very important that the students should always question the validity and accuracy of the numerical techniques as the colorful CFD results often mislead students into trusting all the results that the computer generates. Correlation between the CFD and the ePIV results are fairly high if Figures 11 and 12 are compared. Input data need to be of reasonable quality. For example, the camera parameters should be set to suitable values, and seed density should be sufficient. The differences observed in the CFD and PIV results are very important part of the student learning process. Any differences in the result between the CFD and experiment could be because of many reasons such as seeding density for the ePIV, the choice of the grid and solver in CFD, the resolution of the PIV analysis, the boundary conditions, and so on.

Custom models can be used. For example, the aerofoil model can be used to study flow separation. Fast flow visualization around the aerofoil can be seen in Figure 13. The incidence angle of the wing model can be changed to see the effect on flow separation. The flow separation moved forward as the incidence angle increased. The flow recirculation region can also been seen clearly.

PIV analysis was performed on the aerofoil. The first PIV image can be seen in Figure 14. The second image is similar but with displaced particles. The velocity vectors are superimposed on the image.
FLOWEX™ can also output a shaded plot of the results as can be seen in Figure 15. The wing model is superimposed later with another image program. The boundary layer around the aerofoil can be seen more clearly.

Raw data can be exported for further analysis as can be seen in Table 3.

<table>
<thead>
<tr>
<th>Speed (m/s)</th>
<th>Location</th>
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<tr>
<td>0.1</td>
<td>0.2</td>
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<tr>
<td>0.6</td>
<td>0.8</td>
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<td>1.6</td>
<td>1.8</td>
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<td>2.8</td>
<td>3.0</td>
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<tr>
<td>4.0</td>
<td>4.2</td>
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Table 3. Speed versus location matrix
6. **Outcome assessment**

Table 4 illustrates the way educational objectives – according to the ABET Engineering Criteria\(^{10}\) - could relate to the outcome requirement by the Educational Objectives-Outcomes Correlation Matrix. The skills outcomes and the key to the table parameters are described following Table 4.

<table>
<thead>
<tr>
<th>Knowledge Area(^{11})</th>
<th>A</th>
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<td>2. Fluids concepts</td>
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<td>3. Case studies</td>
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<td>4. Conduct of experiments</td>
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<td>5. Design of experiments</td>
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<td>6. Dimensions, units, values</td>
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<td>7. Experiment optimization</td>
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<td>8. Experiment variables</td>
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<td>9. Flow over obstruction</td>
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<td>11. Flow separation and reattachment</td>
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<td>12. Instrumentation and control</td>
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<td>13. Internal flows</td>
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<td>14. Laminar flow</td>
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<td>15. Mass flow and continuity</td>
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<td>16. Numerical methods and analysis</td>
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| 17. Oral presentations | | | | | | | | | | | | | ✔️
| 18. Particle image velocimetry | ✔️ | ✔️ | | | | | | | | | | | |
| 19. Professional awareness | | | | | | | | | | | | | ✔️
| 20. Professional responsibility | | | | | | | | | | | | | ✔️
| 21. Safety | ✔️ | | | | | | | | | | | | ✔️
| 22. Solution of equations | ✔️ | | | | | | | | | | | | ✔️
| 23. Streamlines | ✔️ | ✔️ | | | | | | | | | | | ✔️
| 24. Teamwork | | | | | | | | | | | | | ✔️
| 25. Technical literature | | | | | | | | | | | | | ✔️
| 26. Technical report writing | | | | | | | | | | | | | ✔️
| 27. Vectors | ✔️ | ✔️ | | | | | | | | | | | ✔️

**Table 4. Objectives and outcomes correlation matrix**

KEY for the Abilities row in Table 4:
A. an ability to apply knowledge of mathematics, science, and engineering
B. an ability to design and conduct experiments, as well as to analyze and interpret data
C. an ability to design a system, component, or process to meet desired needs
D. an ability to function on multi-disciplinary teams
E. an ability to identify, formulate, and solve engineering problems
F. an understanding of professional and ethical responsibility
G. an ability to communicate effectively
H. the broad education necessary to understand the impact of engineering solutions in a global and societal context
I. a recognition of the need for, and an ability to engage in life-long learning
J. a knowledge of contemporary issues
K. an ability to use the techniques, skills, and modern engineering tools necessary for engineering practice

The knowledge areas\textsuperscript{11} in Table 4 that the students are expected to acquire is discussed in more detail in Appendix B.

7. Discussion

The use of PIV technology in fluid flow research is well established and widely accepted. Results from the measurements provide very valuable information about the flow fields to the researchers and engineers of multiple disciplines. Consequently the aerodynamic design of an automobile can be improved and the combustion process in the engine inside the same automobile could be optimized. Nowadays the technology has also been applied in the area of MEMS, biomedical, and physiological research and in many other areas.

Fluid mechanics is a highly visual subject. During the teaching process one must take full advantage of this fact. FLOWEX\textsuperscript{TM} ePIV gives the opportunity to achieve this to its full extent making this technology easily accessible. In an introductory course in fluid mechanics the engineering students are expected to perform laboratory work which helps to correlate the presented theory with hands on experience. Sometimes the experiment precedes theory and in this case the experiment is like a demonstration. Experiment is considered an alternative or a supportive way of learning. The most common method is to teach theory first and then follow up with a laboratory session. The ePIV system is intended to allow educators and students to obtain full understanding of the fluid mechanics theory with experimental visualization. Using the various flow models supplied with the system, many equations and theory can be instructed and presented with the system. Students get hands on experience on what can potentially affect good measurements. They learn the value of setting up an experiment correctly and taking into account various parameters. And once they obtain high quality results, they have a sense of achievement.

PIV is being used to promote science in broader society more and more. An example of this is the work performed at the University of Colorado that combines Art and PIV to promote Fluid Mechanics to students\textsuperscript{12}. One outcome of the course is the recognition by students of the beauty of fluid physics that surrounds us each day, leading to motivation for life-long learning\textsuperscript{12}. It is also stated that the course proved to be very successful in attracting both graduate and undergraduate students, engineering women in particular\textsuperscript{12}. FLOWEX\textsuperscript{TM} can be used to promote fluid mechanics and science in general even to non-science and non-engineering students. It could be used as an effective recruitment tool to science based subjects. FLOWEX\textsuperscript{TM} is able to analyze, interpret and synthesize educational results in formats understandable and useful for non-scientists. University instructors through collaboration with local schools can take this
highly portable tool to high-schools for demonstrations, workshops and educational activities. The high-school students can be introduced to science through this visual tool at an early age.

Postgraduate students teaching fluid mechanics classes at universities may have experience with PIV – and this is becoming more and more common. This tool will lead to exchange of knowledge and experience with PIV and fluid mechanics between the students and the researchers. Student projects using this tool can also lead to limited collaboration between students and researchers. Experiments performed by the students using FLOWEX™ can be disseminated broadly through, presentations to other students in the same institution or other institutions. This will enhance scientific and technological understanding. The users can also design and use their own experiment. Thus FLOWEX™ can be used for limited research. Research based educational materials can be developed. The work performed can encourage student participation at meetings and activities of professional societies.

The low cost and compact size will allow this technology to be used widely and allow the participation of the underrepresented groups. FLOWEX™ is not only intended for laboratories but it can also be used in classrooms, or even remotely over a network or the Internet for online courses. The low cost of FLOWEX™ will allow schools with limited budgets to use the state of the art technology for teaching. Also the highly visual nature of the technology will attract students who learn better from visual interactions rather than theory alone. Non-Ph.D. granting institutions will most likely not have a PIV system in their laboratories. FLOWEX™ is a great opportunity for these types of institutions to introduce their students to PIV technology through teaching. The low cost of the system will allow the instructors to purchase several FLOWEX™ systems immediately or over time. The whole class could be equipped with this latest technology at a relatively low cost. At the moment the price of any commercially available PIV system is prohibitive. Due to its simplicity of operation, low cost and being highly visual, the PIV technology can be used at museums, science centers and similar institutions to develop exhibits in science and engineering. This will involve the public in fluid mechanics education activities.

Physics of fluid flow is a difficult subject. An interactive fluid mechanics study guide would benefit greatly the students preparing for the university to study engineering or other fields of study that require the understanding of the physics of flow. Quick and full comprehension of the physics of fluid flow will motivate students to study engineering, and may even encourage students to follow an engineering career they would otherwise not follow.

8. Conclusion

The ePIV suites is a novel approach that provides significant value to the educator and ultimately the end user i.e. the student, and delivers value in the following ways:

1. The system allows incorporating experiment with theory which stimulates creativity. Creativity is a fundamental component in generating scientific and technological breakthroughs.
2. Students can develop an understanding of fluid flow by an interactive experiment through a computer terminal in the classroom.
3. Motivates the students to be more involved in the learning process and stimulate them to reflect about basic concepts of fluid flow.
4. The students may have a chance to discover the excitement and pleasure of the subject.
5. Improves the quality of education and by increasing customers' image as an educator using the latest technology to teach students fluid mechanics.
6. Provides faculty the latest technology teaching tool at a very affordable price that will allow them to acquire new knowledge and skills and to revise their curricula and teaching practices.
7. It can be used in diverse educational settings because of its effectiveness as an education tool, high-tech appeal, compact size, low cost and safety.

Overall, the design is a simple, economical and student-proof educational tool with a suite of educational software for each grade level, from high school through university. Ultimately the purpose is to combine theory and experiment in teaching. This will not only help the student to master the subject matter quickly but also strengthen the creativity of the students through experimentation.

9. Future work

The ePIV system is the first of its kind to be used in an educational setting. Strategic partnerships with curriculum publishers, schools and universities need to be established. In particular, work with the education professionals very closely to develop testable new ideas for creating learning materials and teaching strategies that have the potential for a direct impact on educational practices. Also work with educational institutes to continue to develop course evaluation tools to measure progress of a typical ePIV course in achieving ABET learning objectives outlined in section 6.

Acknowledgements

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Author’s Note

The educational Particle Image Velocimetry (ePIV) system was developed by Interactive Flow Studies. Further information can be obtained from www.interactiveflows.com. A more detailed description of ePIV can be seen in Patents:

2. “FLUID FLOW COMPUTATION, VISUALIZATION, AND ANALYSIS” - Serial #: 12/130,798
Bibliography

11. http://www.cbe.buffalo.edu/undergrad/Improvement/
## Appendix A – Laboratory Report Considerations

Laboratory report considerations:

<table>
<thead>
<tr>
<th>Accuracy</th>
<th>Reliability</th>
<th>Improvements</th>
<th>Further Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>How accurately were the results measured?</td>
<td>The experiment is reliable if it is repeatable using similar equipment and the same method, and come to the same conclusions. Reliability becomes more difficult as the number of variables increase, and then there may be a variety of possible conclusions.</td>
<td>Could the experimental procedure be improved? Explain what worked well and what didn’t.</td>
<td>Could investigation of another variable improve the conclusions? For example, investigating the effect of varying the fluid temperature on Reynolds number? The variable needs to extend the investigation rather than investigate something that is completely different.</td>
</tr>
<tr>
<td>One or two results may be wrong because the results were misread or written down incorrectly. These need to be identified and not included in the analysis.</td>
<td>The conclusions are only valid over the range of parameters investigated. For example, laminar flow will behave differently to turbulent flow. One can only speculate as to what might happen outside the range of tested values.</td>
<td>Was there enough time to finish the experiments? Could the tests be repeated and thus improved the reliability of the conclusions? State exactly what needs to be repeated, how many times and why.</td>
<td></td>
</tr>
</tbody>
</table>

The conclusions are only valid over the range of parameters investigated. For example, laminar flow will behave differently to turbulent flow. One can only speculate as to what might happen outside the range of tested values.

Was there enough time to finish the experiments? Could the tests be repeated and thus improved the reliability of the conclusions? State exactly what needs to be repeated, how many times and why.

Could the investigation be performed by other types of equipment or different methods which could provide better or different way to verify the conclusions? This usually involves using equipment that is not available for educational use because it is either expensive or too complicated.
Because of faults in equipment or non-ideal capture conditions or parameters there could be a few faulty readings. For example, the seeding density in the flow did not produce the ideal conditions for the CCD camera. These results need to be eliminated before the results are analyzed.

The reliability of the conclusion depends on the overall accuracy of the results. Identify which part of the results is least accurate since this will affect the overall reliability of the conclusion.

Would further incremental measurements improve the results? For example, could a higher resolution vector field produce a smoother velocity graph? Were there equipment limitations that prevented you from doing this?

Are there textbooks where similar experiments are described? If there are, then a simple explanation of the experiment principle and a schematic diagram of the experiment from the textbook would be sufficient.

There may be an anomaly which could be a feature of the results that was unexpected and does not match prediction. If there are too many variables, anomalies may be random and be difficult to reproduce experimentally. What could be the scientific reasons behind the anomalies?

Pay close attention to the control variables. Note the variables that were difficult to control or impossible to measure that could affect the results.

Could a larger range of variables broaden the conclusions? What further variable ranges could be tested? Were there limitations of time and/or equipment?

How about inventing a better experiment which has different types of sensors, controls etc.

If, say, a velocity profile is plotted, poor results with a low accuracy will not give a graph with a smooth trend. These results are just inaccurate. They should not be identified as anomalous.

Could the reliability of the results be improved by altering control variables’ values or better monitoring?

If the experiment was simple, then the chances are there won't be any anomalous results. State why?

How could the ePIV system be improved?
Appendix B – Knowledge Areas

The knowledge areas in Table 4 that the students are expected to acquire are:

1. Analysis of experiments:
   a. Quantitatively generate a velocity vector field.
   b. Plot data in graphical format with label and units of variables – e.g. shaded plot.
   c. Extract data from the results and plot in linear graphical form – e.g. velocity versus location.
   d. Calculate the average flow rate at a particular cross section.
   e. Understand variability in experimental results.
   f. Export velocity data into Excel or another analysis software to perform further calculations – e.g. calculate vorticity.

2. Fluids concepts:
   a. Understand laminar flow, turbulent flow, Reynolds number, boundary layer, shear layer, strain rates, shear rate, streamlines, vorticity, viscosity, flow separation, continuity, recirculation, flow acceleration and deceleration.

3. Case studies:
   a. Understand the various flow phenomena observed in the six obstructions supplied with the system.
   b. Ability to design custom flow models to create custom case studies.
   c. Ability to follow the design optimization process as shown in Figure 1.

4. Conduct of experiments:
   a. Develop research skills.
   b. Using a professional laboratory notebook.
   c. Understand the importance of keeping accurate records.
   d. Understand importance of reading the manual and following operating instructions.
   e. Ability to change the seeding density incrementally and observing the PIV results.
   f. Following the sequential process of removing bubbles – if any – as per the instruction manual.
   g. Recording PIV data for further analysis and report writing.
   h. Ability to vary the flow rate and direction.
   i. Ability to interchange the flow models.
   j. Ability to use FLOWEX™ software and optimize PIV parameters.

5. Design of experiments:
   a. Develop creativity.
   b. Understand the importance of steady state and transient flows.
   c. Understand the importance of optimizing seeding density.
   d. Understand the importance of selecting the best flow model to observe particular flow phenomena.
   e. Understand the effect of initial flow profile on the downstream flow phenomena.
   f. Understand the effect of gravity on the flow phenomena.
   g. Understand the effect of viscosity and temperature on flow phenomena.

6. Dimensions, units, values:
   a. Understanding standard units – e.g. Standard International (SI), American Engineering (AE) units.
   b. Ability to convert between units.
c. Understand significant figures.
d. Understand the importance of units.
e. Understand conversion from camera pixels per second and meters per second.
f. Understand scaling – e.g. camera lens magnification.
g. Understand dimensionless parameters – e.g. Reynolds number.

7. Experiment optimization:
a. Ability to optimize the seeding density.
b. Ability to optimize streamline capture, using the camera control variables in FLOWEX™ software.
c. Ability to optimize flow rate to obtain PIV results.
d. Ability to optimize PIV analysis variables in FLOWEX™ software.

8. Experiment variables:
a. Understand flow variables such as mass flow rate, flow direction, flow viscosity, temperature and pressure.
b. Understand ePIV variables such as seeding density, time between frames, brightness, exposure, gain, shift and window size.

9. Flow over obstruction:
a. Understand flow acceleration through a restriction.
b. Understand flow boundary layer effect for different obstructions.
c. Understand flow separation and reattachment behind various obstructions.
d. Understand drag.

10. Flow recirculation:
a. Understand vorticity.
b. Understand flow recirculation phenomena for instantaneous and gradual change of flow direction.
c. Understand flow vorticity at various flow rates.

11. Flow separation and reattachment:
a. Understand the flow separation phenomena for various obstructions.
b. Understand the flow separation and reattachment at different flow rates.

12. Instrumentation and control:
a. Understand the operation of the ePIV system.
b. Knowledge of the flow rate and instantaneous flow direction controls.
c. Knowledge of the limitations of the ePIV instrument.

13. Internal flows:
a. Understand boundary layer.
b. Quantitatively obtain velocity profiles of flow bounded by two walls.
c. Understand the importance of initial velocity profile – e.g. boundary condition for CFD analysis.

14. Laminar flow:
a. Knowledge of Reynolds number definition – e.g. Re<2000 is considered laminar flow in internal flows.
b. Understand the difference between laminar and turbulent flow.
c. Understand the importance of laminar flow in boundary layers and mixing.

15. Mass flow and continuity:
a. Quantitatively validate continuity.
b. Calculate mass flow rate – e.g. density x average speed x cross sectional area.
c. Compare calculated and measured flow rate (ePIV-FR option is required to measure flow rate directly). Understand why there is a difference if any.

d. Understand the effect varying flow rate on flow phenomena – e.g. flow separation.
e. Determine the limitations of PIV at varying flow rates – e.g. fast versus slow flows.

16. Numerical methods (e.g. CFD if available) and analysis:
   a. Ability to use ePIV to validate CFD.
   b. Use experimental ePIV data for input boundary conditions in CFD.
   c. Optimize a design model with CFD and test with ePIV.
   d. Linear interpolation of ePIV results.

17. Oral presentations:
   a. Ability to give an effective presentation within the allotted time.
   b. Use fluid mechanics terminology correctly during the presentations.
   c. Ability to utilize the full potential of ePIV system to produce a highly visual presentation.
   d. Demonstrate full understanding of the subject.
   e. Prepare a novel and interesting presentation.

18. Particle image velocimetry:
   a. Knowledge of principles of PIV – e.g. cross correlation.
   b. Understand the importance of seeding density.
   c. Knowledge of the strengths and limitations of PIV.
   d. Understand the PIV process and parameters – e.g. frame rate, resolution.
   e. Knowledge of PIV applications – e.g. vorticity visualization and analysis.

19. Professional awareness:
   a. Understanding the importance of fluid mechanics in worldwide applications.
   b. Knowledge of PIV technology widely used in research at Universities and companies.

20. Professional responsibility:
   a. Understand professional responsibility – e.g. ethical conduct.
   b. Ethical behavior when performing the experiments and writing the report.

21. Safety:
   a. Knowledge of laboratory safety requirements and apply safety practices.
   b. Knowledge of laser hazards.
   c. Use of safety glasses and use of a laboratory coat.
   d. Knowledge of material safety data sheet (MSDS).
   e. Knowledge of the location of the first aid kit.
   f. Understand safety issues of industrial or research PIV systems – e.g. Class IV lasers.

22. Solution of equations:
   a. Ability to solve simple flow equations – e.g. continuity.
   b. Calculate Reynolds number.

23. Streamlines:
   a. Understand the importance of visualizing flow using streamlines.
   b. Ability to obtain streamlines using the ePIV system.
   c. Demonstrate the effect of instantaneous flow direction.
   d. Explain the flow phenomena qualitatively using streamlines – e.g. flow separation.

24. Teamwork:
   a. Develop team coordination, consensus decision-making, communication, group collaboration, planning, and execution skills.
b. Take turns in operating the ePIV system and FLOWEX™ software.

25. Technical literature:
   a. Read Flow Theory sections in FLOWEX™.
   b. Understand the role and value of technical literature.
   c. Ability to use technical literature.

26. Technical report writing:
   a. Knowledge of structure of a laboratory report.
   b. Importance of keeping laboratory notes on the experiment.
   c. Ability to write a technical report.
   d. Demonstrate higher order thinking in analysis of data and discussion.

27. Vectors:
   a. Ability to plot vector field.
   b. Use visual validation method during PIV analysis – e.g. identify vectors outside trend.
   c. Knowledge of the meaning of vectors – e.g. vector information includes direction and magnitude of flow.
   d. Understand the importance of vector resolution in flow analysis.
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