Strathprints Institutional Repository

The Development And Application Of Time Resolved PIV At The University Of Strathclyde

M Stickland*, T Scanlon*, T Vidinha*, W Dempster*, R Jaryczewski**

* Department of Mechanical Engineering, University of Strathclyde, Glasgow.
** Dantec Dynamics Ltd, Royal Portbury, Bristol.

ABSTRACT

This paper describes the development of time resolved particle image velocimetry (PIV) within the Department of Mechanical Engineering at the University of Strathclyde. The Department's first PIV systems were developed on a limited budget and used existing and second hand equipment. The original technique which, employed 16mm high speed cinematography, is described. The introduction and development of low cost systems employing high speed digital video (HSDV) is discussed and, finally, the Department's new time resolved PIV system, supplied by Dantec Dynamics, is introduced. For each of the PIV systems that have been developed a critical analysis of their functionality is given and samples of the data that they have been produced are shown. Data are presented from systems such as de-rotated centrifugal impellers, air bubbles growing in columns of water, pulsatile jets and vortex shedding.

1. Introduction

1.1 Bubble Flows

Researchers in the Energy Systems Division of the Department Of Mechanical Engineering at the University Of Strathclyde were first drawn to the application of time resolved PIV because of their study of bubble formation, growth and detachment as part of a funded research program into the loss of coolant accident (LOCA) which could occur within a pressurised water reactor (PWR)**[1]**, figure 1.

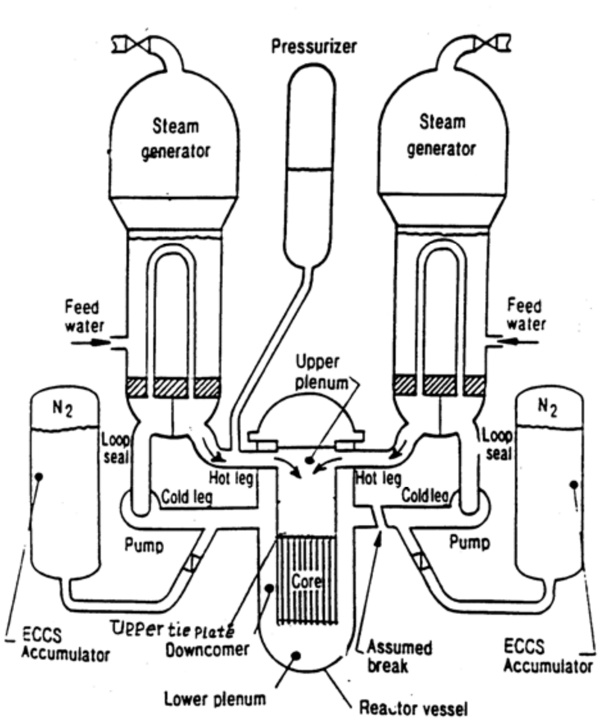

Figure 1: PWR Schematic

During a LOCA a breach within the cold leg of the PWR may occur and cause the primary coolant within the reactor to be forced out of the system. To facilitate the required heat dissipation cold water is flushed into the core from the emergency core cooling system (ECCS) accumulators. The rate at which this cooling water can enter the reactor through the hot legs is limited by the steam being generated within the core trying to force its way out through the hot legs. Steam continues to be generated until there exists a pool of water on the upper tie plate in which the steam, generated in the core, condenses. The depth of the pool and the liquid thermal conditions required to completely condense the steam generated is dependent upon the rate at which the steam is generated and the size and shape of the bubbles.

Initial research was undertaken to study and model the growth, detachment and heat transfer characteristics of steam bubbles in water. This utilised a shadowgraph technique to capture two dimensional images of the bubbles by a high speed cine camera as they developed.

It was decided to undertake some flow measurement around a growing bubble by PIV. Because the bubble growth is a highly transient phenomena the standard PIV method of taking single autocorrelation images with a CCD or 35mm camera was inappropriate as they would simply supply snapshots of the whole process. It was therefore decided to utilise high speed cine as this would capture a complete cycle of growth and detachment and allow for the flow field to be determined at a later stage It was considered that the initial application of this technique should be applied to an air bubble growing in water for the sake of safety and simplicity.

The particles in the flow were illuminated by a laser sheet produced by a 5W Spectra Physics 165 Argon Ion laser and cylindrical lens. Typically only 2.5W of laser power were required for imaging purposes. The process of bubble formation was filmed by an Hitachi 16HM high speed camera at frame rates of between five hundred and a thousand frames per second. Air flow was provided by a Charles Austin

CAPEX 2 membrane air pump at rates between 200 and 1100 cm^3 per minute measured by a rotameter. The water column was 150mm square section and 300mm high manufactured in glass with a 4mm orifice at the base. A diagram of the experimental setup is shown in figure 2.

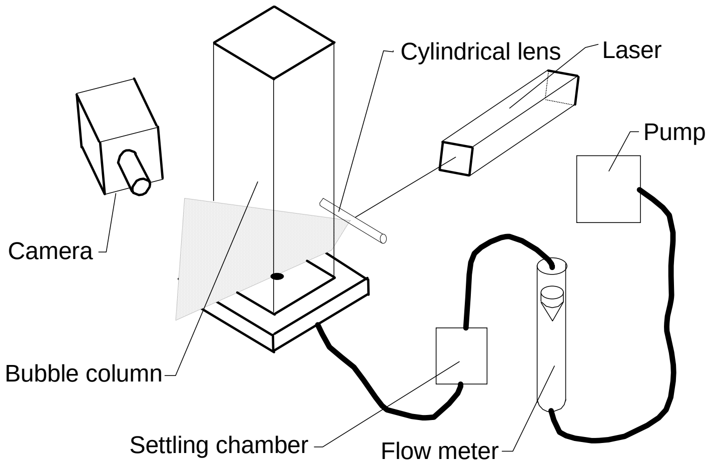

Figure 2: Experimental setup

Images were digitised by projecting the 16mm negative image onto a screen and grabbing with a Sony XC75 768 x 494 pixel monochrome CCD camera connected to a Matrox frame grabber card in a 486SX25 PC. The digitised images were analysed by Optical Flow Systems VidPiv PIV analysis Software by cross correlation on a 486DX266 PC. A typical image may be seen in figure 3.

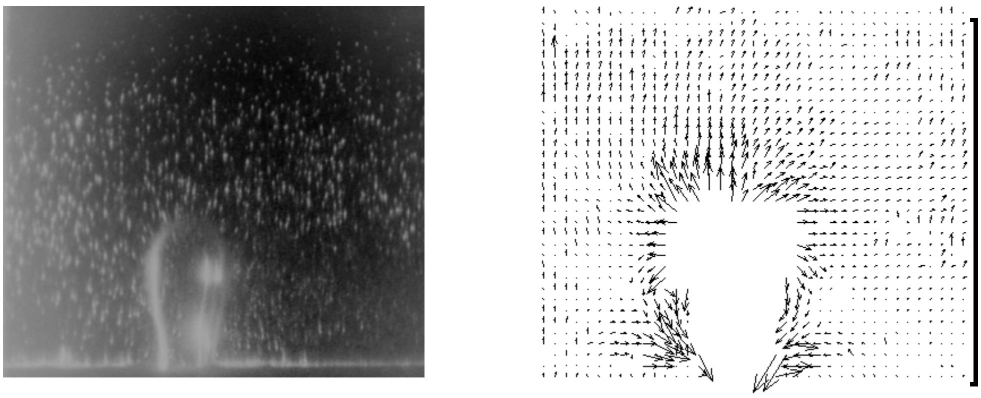

Figure 3: Original bubble PIV data

The process was extremely time consuming and took several days between taking the images and producing the vector map. To speed up the process a high speed digital video was purchased. The Kodak Motioncorder was one of the first relatively low cost, approximately £10k, high speed digital videos. However, whilst it stored the data digitally it could only provide an analogue, PAL, output.

The process of bubble formation was now filmed by the Kodak Motioncorder which had a capability of recording at frame rates up to 600 frames per second. The images were digitised by a Matrox frame grabber card in a 486DX266PC. The digitised images were analysed by Optical Flow Systems VidPiv PIV analysis Software by cross correlation on a Pentium P200 PC. Typically, the images were acquired at 240 frames per second and a resolution of 256x256 pixels. The time between taking the images and producing a single vector map had reduced to approximately an hour [2]. The data was of good quality and was used to validate some simple, two dimensional, inviscid models of the flow field, figure 4.

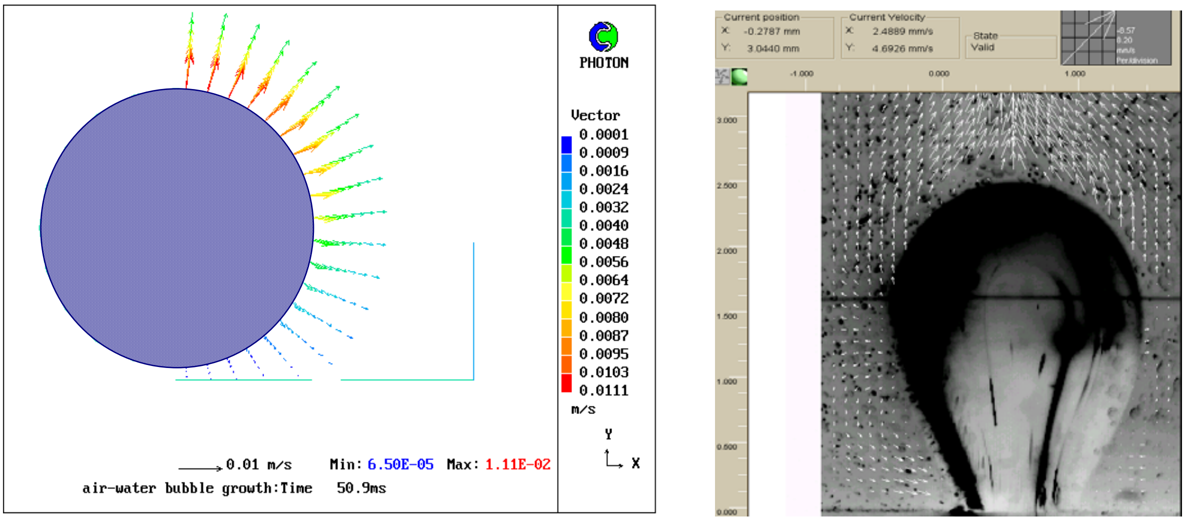

Figure 4: PIV image and vector map acquired by Kodak Motioncorder

In early 2000 a Photron Fastcam super 10KC was acquired. The Fastcam is a high speed digital video capable of capturing up to 10k images per second It has a higher resolution that the original Motioncorder and can digitally down load directly to a PC via a SCSI 2 link in .bmp format. Illumination was still provided by a 5W Spectra Physics Argon Ion laser and analysis was by cross correlation using VidPIV V2.41 from Optical Flow Systems of Edinburgh. The time from acquisition to production of a single vector map had now reduced to just ten minutes.

2. Time Resolved PIV system

The quality of the images and data acquired by the original systems were remarkable considering the rather haphazard way that the system had been developed over a number of years. In 2000, an application was made to the Engineering and Physical Sciences Research Council for £137k to allow the purchase of a specifically designed system.

The system acquired from Dantec Dynamics consisted of a Lee Lasers LDP 100MQG diode pumped Nd:YAG Laser, Photron Ultima high speed digital video (HSDV), Flowmanager analysis Software and TimeResolve trigger and synchronistion system. The Nd:YAG laser is capable of pulse repetition rates up to 50 kHz with 5mJ per pulse at 10 kHz. With a pulse width of approximately 190 ns. It requires a 25A single phase power supply and has an integral chiller unit on the power supply which does not require an external water supply for cooling. The Photron Ultima has a maximum resolution of 1024x1024 pixels at frame rates up to 500 frames per second reducing to 512x128 at 4000 frames per second. The time resolve synchronisation system allows the laser and camera to be slaved together to run in either single shot mode or double pulse, frame straddling, PIV mode. Figure 5 shows the two modes in which the laser may be triggered.

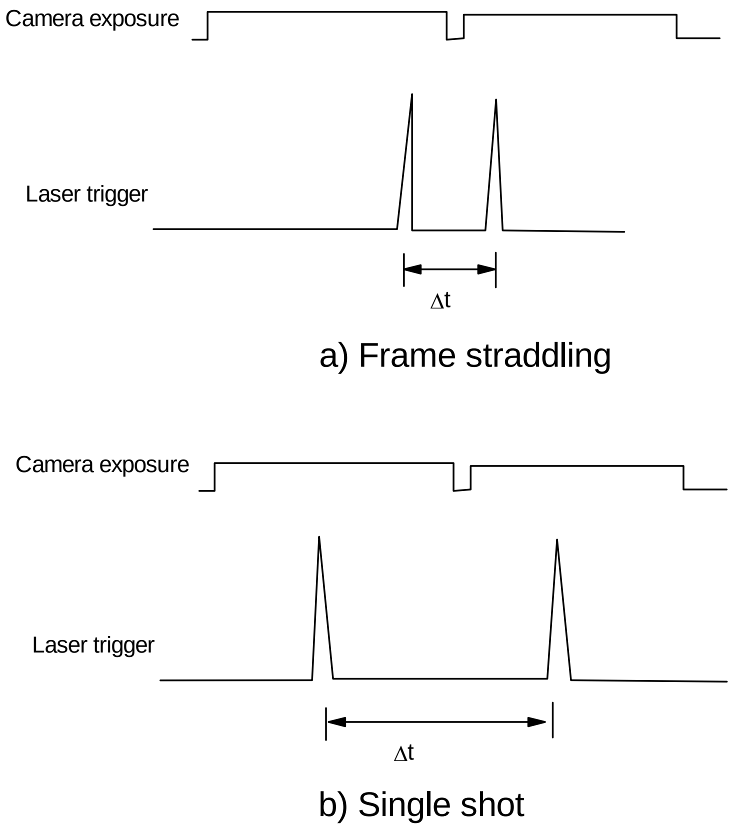

Figure 5: Camera and Laser trigger sequencing

2.1 Single shot mode.

In the single shot mode the laser is synchronised to fire a single 190 ns pulse in the centre of each camera exposure. The time delay between images is therefore regulated by the exposure rate of the HSDV – from 16 ms to 25μs. This allows the cross correlation of images for relatively low speed flows at high resolution but for higher speed flows the resolution will, necessarily, be reduced due to the higher frame rate of the camera. For high resolution at higher speeds frame straddling was required.

2.2 Frame straddling – PIV mode

In the frame straddling mode the laser is triggered just before the end of the first exposure and shortly after the start of the second exposure of the HSDV. In this mode it is possible to vary the time between exposures from 20μs seconds up to 200μs seconds allowing the measurement of relatively fast flows. As the time delay is now independent of the camera frame rate high resolution images may be acquired.

2.3 Laser power regulation

In the frame straddling mode it is necessary to control the power in each laser pulse. As the pulses are not regularly spaced the first pulse will contain an excessive amount of power whilst the second pulse, having less time for the laser to charge, will be relatively weak. To balance the power in each pulse the laser is discharged at a specified time before the first pulse. This discharge time varies with the repetition rate and the time delay between pulses and is estimated by analysing the laser output via a high speed photo diode and oscilloscope. Care must be taken not to run the laser at full power at low repetition rates (less than 5kHz) as this may damage the second harmonic generator (SHG) crystal. The pulse regulating discharge ensures that the SHG crystal will not be damaged.

3.0 Sample data

Below are some images and the associated data that have been collected by the system. The data are just small selections from much larger data sets. Animations of theses data sets may be found on the accompanying CD ROM or by visiting htttp:\\www.homepages.strath.ac.uk\~clcs20\

3.1 Bubble Formation.

Figure 6 shows the vector field surrounding an air bubble growing from a submerged orifice. The orifice diameter was 6mm and the air volume flow rate 90 cc/min. The data was acquired at 1000 frames per second in single shot mode. Typically, between 50 and 100 vector maps were acquired for each bubble formation [3].

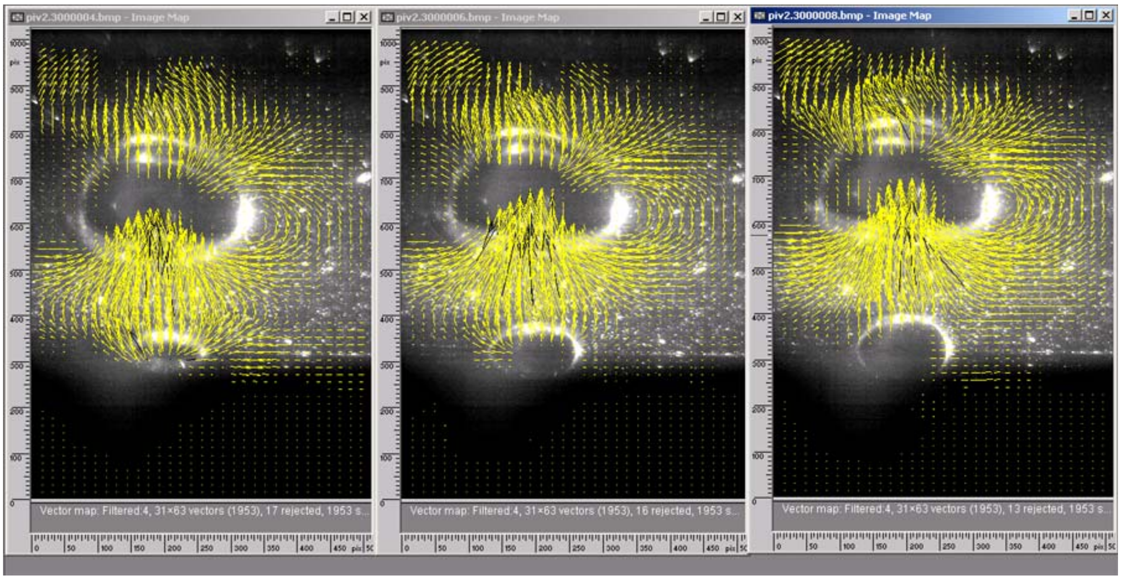

Figure 6: Vector field around a bubble growing at a submerged orifice

3.2 Derotated impeller flows

The flow patterns between the blades of an impeller can be turbulent and constantly changing with time. This turbulence will lead to poor performance of the impeller and, if excessive, may lead to the early failure of the impeller or to the creation of unacceptable noise. It is, therefore, to the impeller designers advantage to discover the nature and cause of these secondary flows so that they might be eliminated

Analysis of secondary flows is difficult when the observer remains stationary relative to the impeller as they are hidden within the dominant primary flow. If, however the observer is able to rotate in the plane of the impeller at the same rotational speed then the impeller appears to be stationary, the primary flow disappears and the observer only sees the secondary flow field relative to the stationary impeller.

The authors have been able to obtain the relative view of a flow field in an impeller by the use of an image de-rotator. The image derotator optically rendered completely stationary the image of the rotating impeller. The derotated view of the impeller was then analysed by particle image velocimetry to provide the relative velocity field within the radial blade passages of the centrifugal impeller [4][5].

Water was used as the working fluid, seeded with 50μm diameter polyamid particles. Data was acquired at 1000 Hz in frame straddling PIV mode with a pulse separation of 100 μs. Figure 7 shows the velocity vectors on the pressure and suction sides of an impeller blade rotating at 650 rpm.

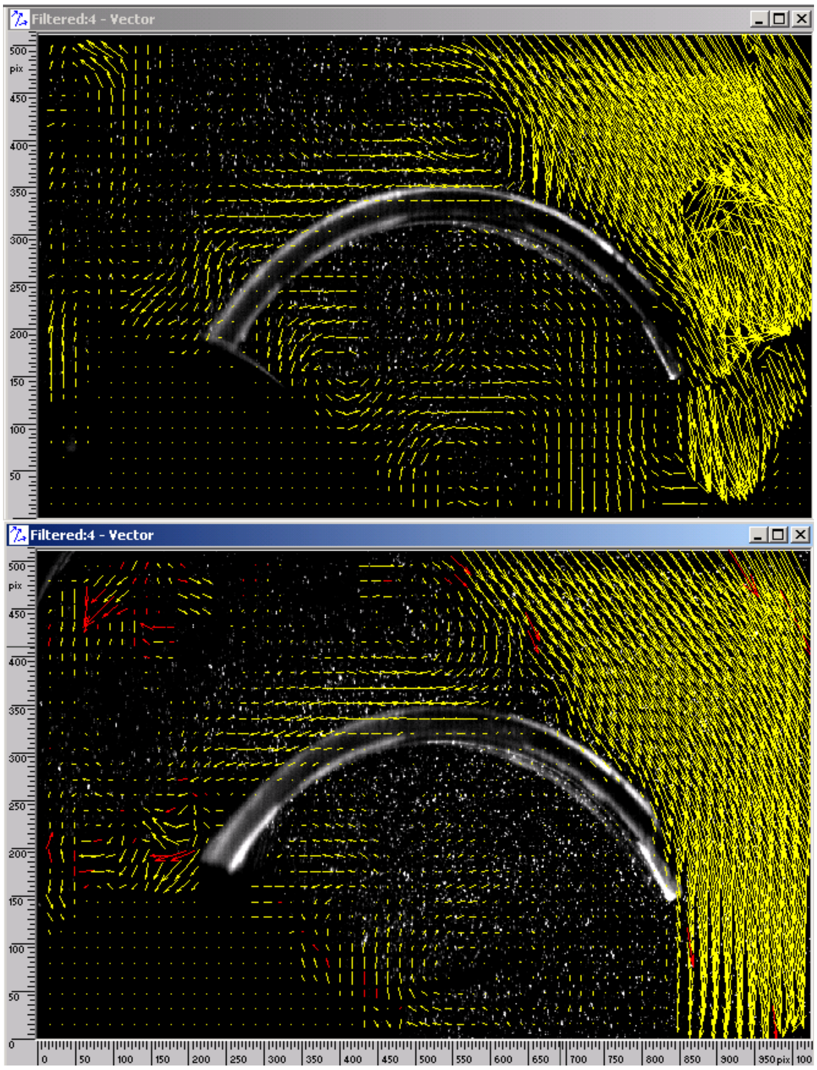

Figure 7: Velocity vectors on the pressure and suction sides of an impeller blade.

3.3 Pulsatile jet flow

Figure 8 shows the velocity vectors of a jet of fluid issuing into a tank of water. The diameter of the jet was 5 cm and the jet was pulsed sinusoidally at approximately 1Hz. The data was acquired in frame straddling PIV mode with a pulse separation of 200 µs at a frame rate of 1000Hz. The images shown were acquired just as the jet started issuing into the tank and clearly show the starting vortex being developed.

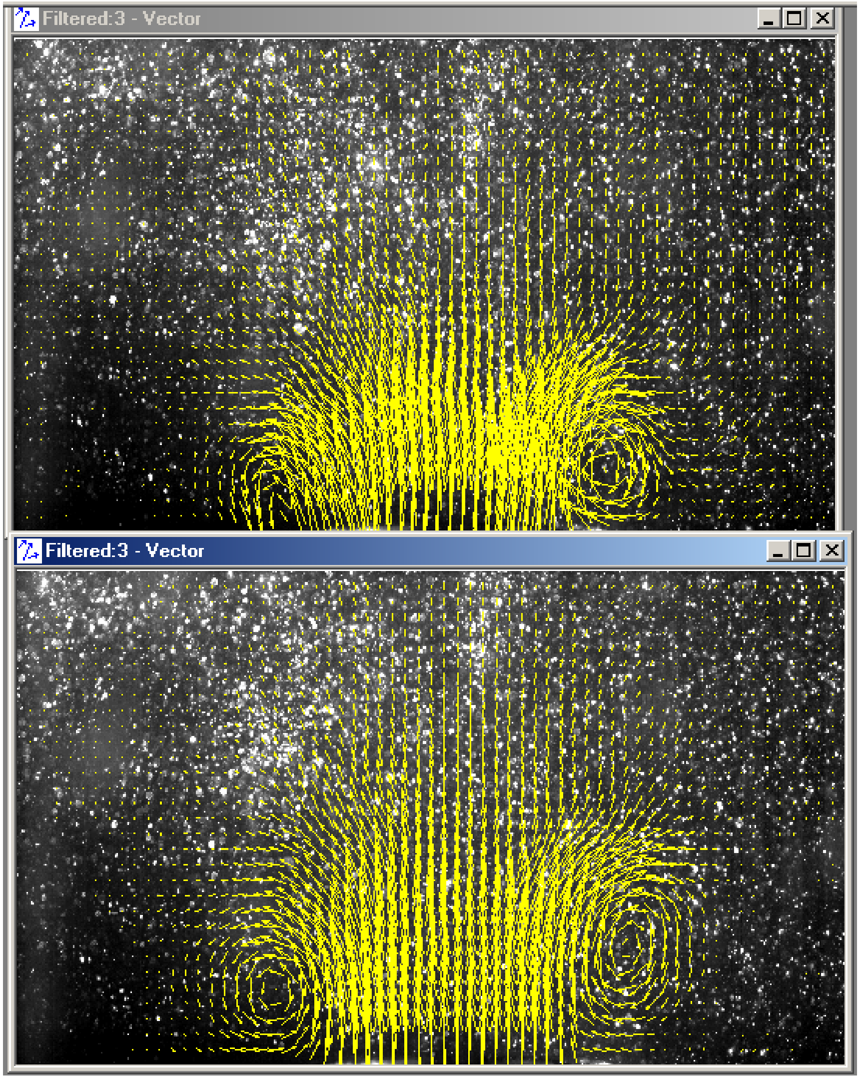

Figure 8: pulsatile jet flow.

4. Discussion

The Department of Mechanical engineering has, for several years, persevered with the development of time resolved PIV. The original systems were rather crude and required an excessively long time to produce a limited number of data sets. However, the development of solid state pulsed lasers and digital high speed video and high speed digital computers has allowed much of the data acquisition process to become automated. The increased power of the light sources and the increase in resolution of the cameras has also allowed a significant improvement in the quality of the raw data produced. Combined with the massive increase in the computer power available in a relatively cheap PC this has allowed the analysis of the data sets to be accomplished within seconds. The development of digital cameras capable of acquiring data at over 10kHz has now even made it possible to contemplate the statistical analysis of these data sets to provide turbulence data.

The data shown in this paper are, by necessity, a small part of much larger data sets. The benefits of time resolved PIV can only truly be appreciated by studying these large data sets when the structure of transient flows can be fully appreciated.

5. Conclusions

The time resolved PIV system used by authors has successfully measured several different transient flow fields. The range of different transient flow phenomena which will benefit from measurement by this new technique is almost limitless and the possibility of utilising it for more fully understanding the nature and structure of turbulence is intriguing

5. References

[1.] Stickland M T, Dempster W, Lothian L, “PIV Studies of Bubble Growth and Detachment by High Speed Photography”. 22nd International Symposium on High Speed Photography and Photonics, Santa Fe, USA, SPIE, October 1996.

[2.] Dempster Wm, Stickland M. "Particle Image Velocimetry Studies of Bubble Growth and Detachment by High Speed Video Photography".2nd International Symposium on Two Phase Flow Modelling and Experimentation, PISA, May 23-26 1999 Vol III pp 1365-1370ISBN:88-467-0177-3

[3.] T Vidinha, W Dempster, M Stickland**,** “Liquid Velocity Field Measurements during Bubble Formation and Detachment at an Orifice”. EALA Conference, Sept 2001, Limerick.

[4.] M Stickland, Blanco E, J Fernandez, Parrondo J, T Scanlon, “A Numerical And Experimental Analysis Of Flow In A Centrifugal Pump” The 2002 Joint US ASME-European Fluids Engineering Summer Conference. July 14-18, 2002, Montreal

[5.] M Stickland, J Fernandez, T Scanlon, P Waddell, **“**Mapping The Velocity Field In A Pump Impeller Using High speed digital video, Image de rotation and Particle Image Velocimetry”. EALA Conference, Sept 2001, Limerick