Particle image velocimetry studies of bubble growth and detachment by high speed photography

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ABSTRACT

An understanding of bubble flows is important in the design of process equipment, particularly in the chemical and power industries. In vapour-liquid processes the mass and heat transfer between the phases is dominated by the liquid-vapour interface and is determined by the number, size and shape of the bubbles. For bubble flows these characteristics are often controlled by the generation mechanisms and, since bubble flows are often generated at an orifice, it is important to determine the controlling parameters which dictate how bubbles grow and detach. For bubbles growing at orifices the liquid displacement is an important feature and affects the pressure distribution acting on the bubble and the heat and mass transfer that may occur at the bubble interface. Therefore, in this study, the characteristics of the liquid velocity field are studied experimentally using Particle Image Velocimetry (PIV) during growth, detachment and translation of a bubble being generated at an orifice supplied with a constant mass flow rate of air.

The process is transient and occurs over a period of approximately 50 msecs. In order to map the transient flow field a combination of high speed cine and cross correlation PIV image processing has been used to determine the liquid velocity vector field during the bubble growth process. The paper contains details of the PIV technique and presents several of the velocity vector maps calculated.

KEY WORDS

two phase flow, particle image velocimetry, bubbles, high speed photography

1. INTRODUCTION

Researchers in the Energy Systems Division of the Department Of Mechanical Engineering at the University Of Strathclyde were first drawn to the 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), figure 1.

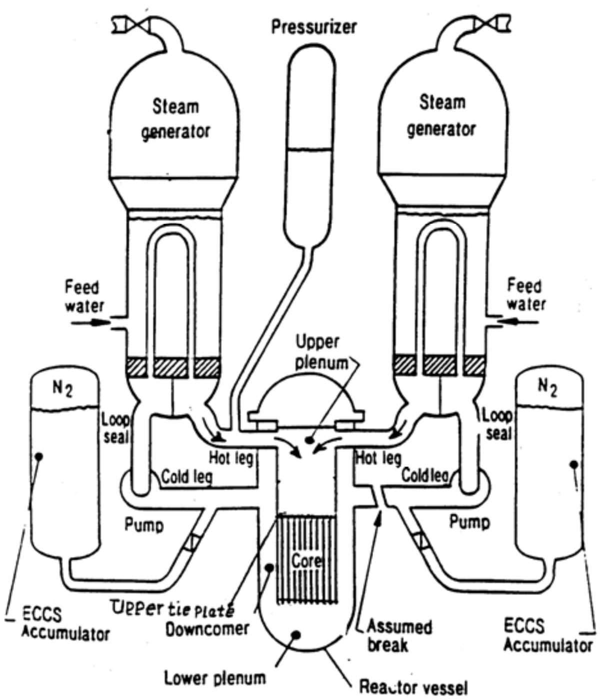


Figure 1: PWR Schematic

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. The coolant water also acts as the moderator for the nuclear reaction hence the reactor will shut down. However there is still a residual power within the core and if this heat is not dissipated the reactor core will be damaged. To facilitate the required heat dissipation cold water is flushed into the core from the emergency core cooling system (ECCS) accumulators. Figure 1 shows the coolant circuit installed in the PWR at Sizewell in Suffolk, England . In this type of reactor the ECCS water is forced into the core via the cold legs through the lower plenum and into the core. However earlier European PWRs also forced the ECCS water in through the hot legs onto the upper tie plate. The upper tie plate consists of many holes through which the fuel assemblies pass and are held in place. 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. The 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.

P = 1 bar
Δt_{sub} = 10K
m_s = 5x10^{-6} kg/s
water level = 36 mm
orifice diameter = 2 mm

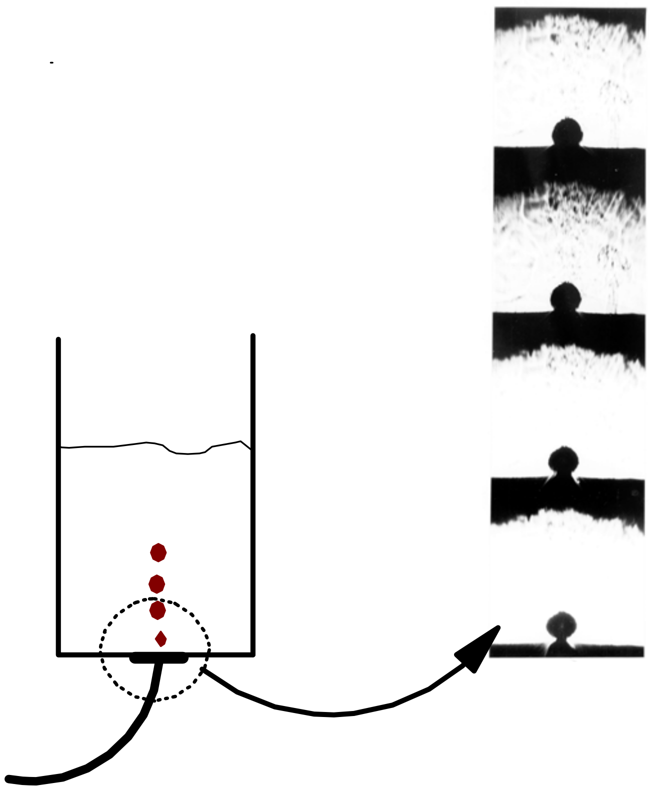
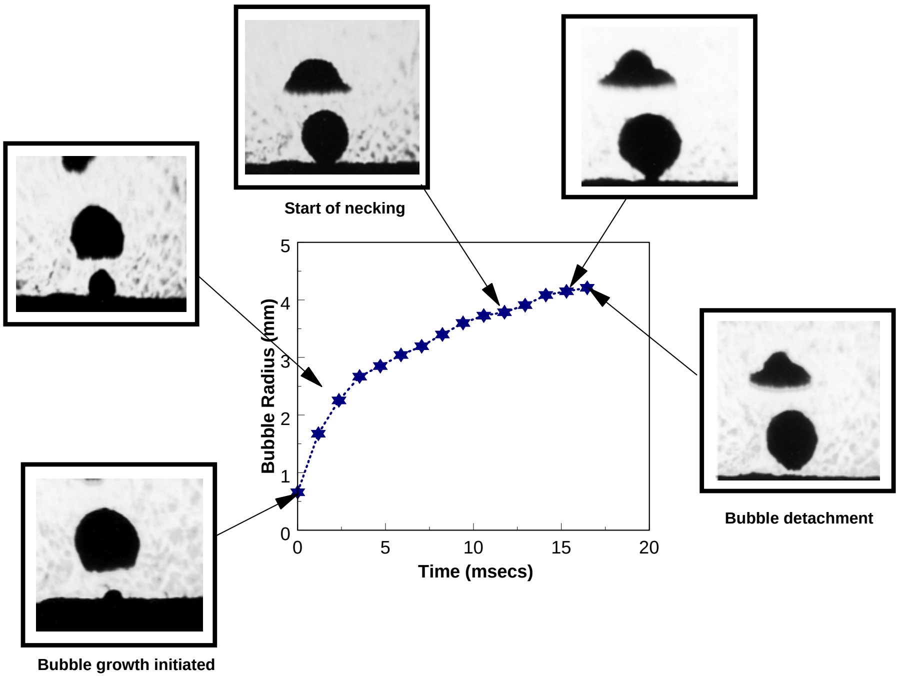


Figure 2: shadowgraph of steam bubble

The periphery of the shadowgraph image of the bubble was digitised manually and the volume of the bubble calculated by assuming the bubble to be axially symmetric. From this information the motion of the bubble centroid was inferred and the rate of condensation and hence heat transfer calculated[1]. Figure 3 shows the measured bubble radius with time and the collapsing bubble shapes at various positions



Bubble growth between initiation and detachment

Figure 3

The bubble was modeled as a translating expanding control volume and the resulting potential flow determined by potential flow theory by the supposition of sources and sinks whilst the heat transfer was calculated by a finite difference technique on a moving grid fitted to the predicted bubble shape. It was noted that the rate of growth, motion and the heat transfer characteristics of each bubble were dominated by the velocities within the liquid flow field surrounding the bubble.A typical flow field of the liquid calculated for a growing bubble may be seen in figure 4.

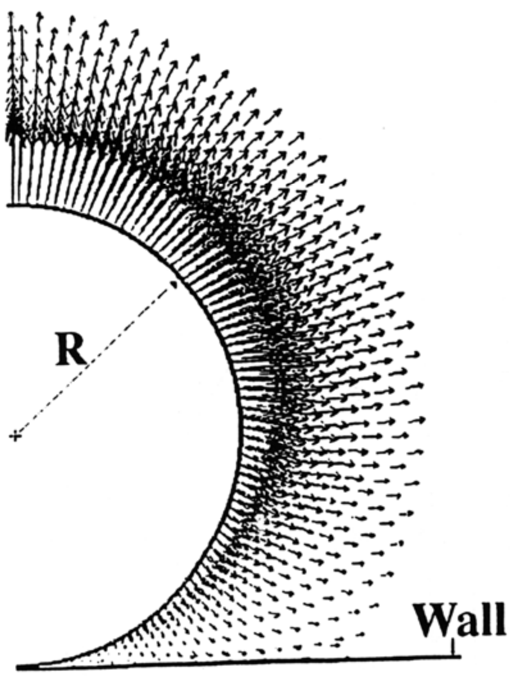


Figure 4: Potential flow field around growing bubble

Unfortunately information about the velocities in the flow field around the bubble was not available from the original shadowgraph work so 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 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.

2. PARTICLE IMAGE VELOCIMETRY

Particle image velocimetry is, now, a common technique which allows the whole flow field's velocity to be mapped instantaneously by computationally analysing a picture of the flow field. This image usually has multiple exposures of the flow which has been seeded with small particles and illuminated by a thin sheet of laser light. The analysis of a single image of the flow field is referred to as autocorrelation. An alternative to autocorrelation is to analyse two sequential images of the flow field; referred to as cross correlation.

2.1 CROSS CORRELATION

Cross correlation produces a vector map of the flow field by analysing pairs of sequential images. In this process the computer algorithm calculates the direction and magnitude of the displacement of a particle, or group of particles, between exposures. If the time between exposures is known then, combined with an analysis of the direction of the displacement, the velocity of the particle and hence the flow in that region is known.

Cross correlation analysis is advantageous because it does not create any directional ambiguity within the vectors calculated and is capable of measuring extremely low as well as a wide range of velocities.

PIV has been applied to numerous flows ranging from low speed bluff body flows[2], high speed flows[3], combusting flows[4], two phase flows[5] and turbomachinery[6]. The technique is now an established tool within the experimental fluid mechanics community and will not, therefore be described in detail within this paper. For information on PIV in general the reader is recommended to consult the paper by Gray[7].

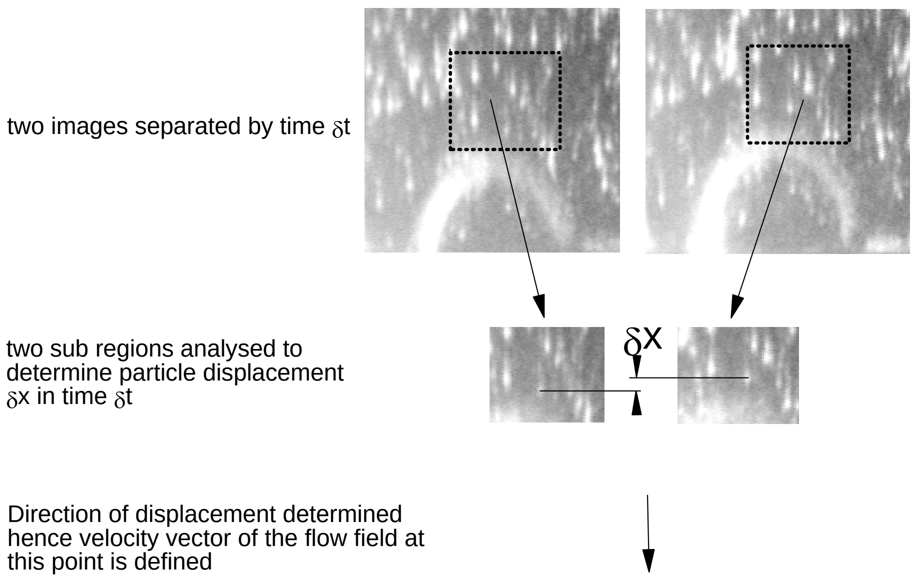


Figure 5: Cross correlation technique

3. EXPERIMENTAL EQUIPMENT

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 a 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 6.

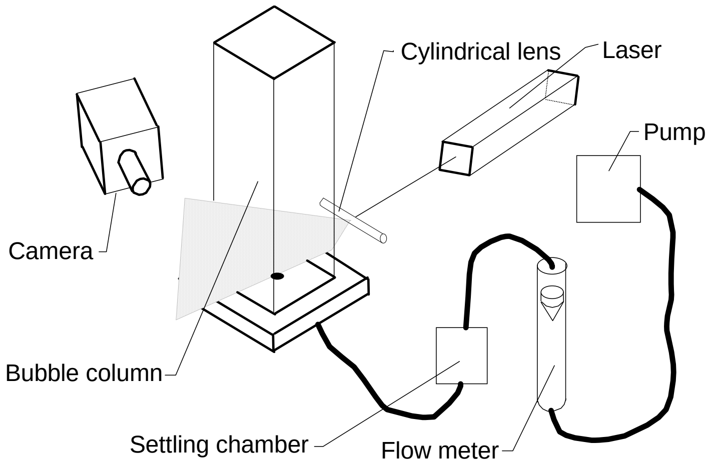
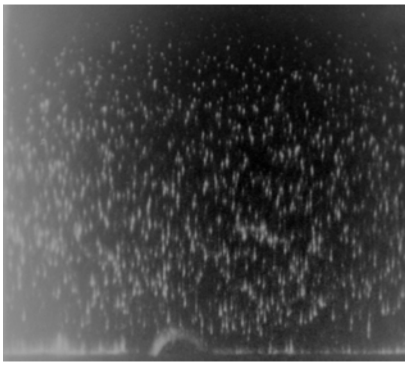
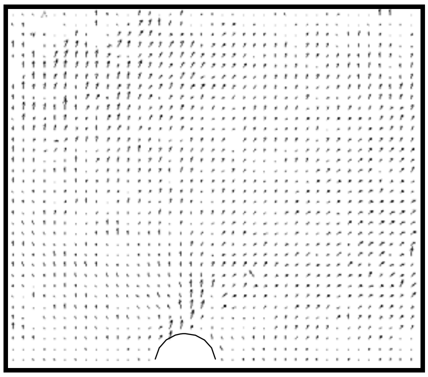


Figure 6 Experimental setup

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. To compensate for magnification within the optics a reference grid was filmed and digitised to give the required scaling information

4. RESULTS

When the acquired images had been digitised from the cine film pairs of images were analysed by cross correlation to yield the vector field around the emerging bubble. It was necessary to select pairs of images with sufficient particle displacement to record a vector therefore every second image was cross correlated. The examples shown below in figures 7 to 14 were acquired at 750 frames per second with an air flow rate of 200 cm^3/min. Timing is given from the first sign of bubble growth and the image is the first of the pair used for cross correlation.

Figures 7 and 8: 2.7ms

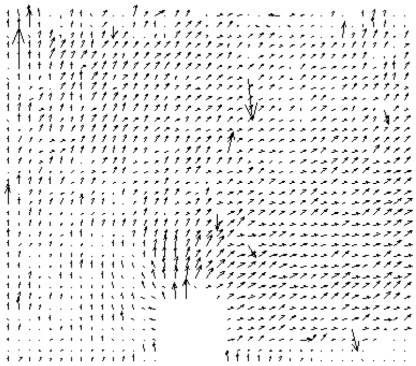
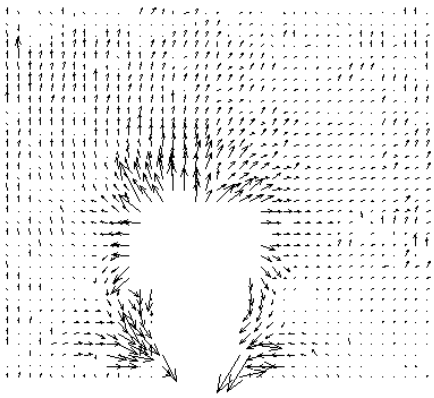
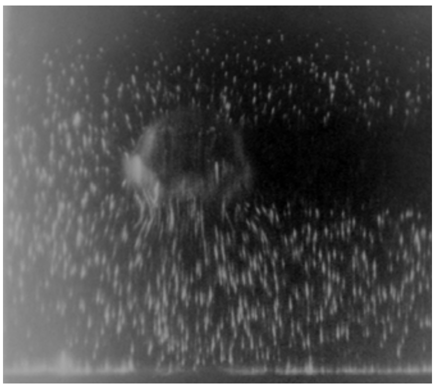
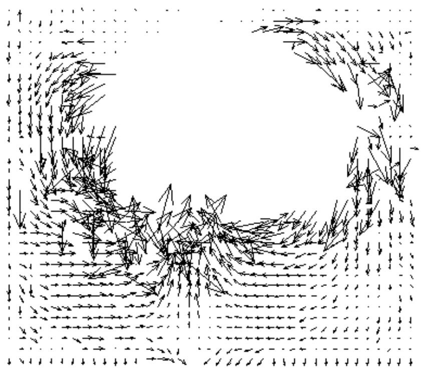



Figure 9 and 10: 21.33ms

Figures 11 and 12: 45.33 ms

Figures 13 and 14; 56.00 ms

5. DISCUSSION

Figures 7 to 14 clearly show that this technique has the capability to measure the flow field around a bubble from growth to separation. It is interesting to note from these flow maps that the whole flow field is never stationary and there always exists turbulence, both small scale and large scale, from the preceding bubbles. The current potential flow theory used to compute the flow field is unable to model this phenomena and hence the effect of turbulence will need to be considered in future work

It may be seen from figures 7 to 14 that the flow field in close proximity to the bubble surface was difficult to measure. This was due to the glare from the reflected laser light masking the presence of seeding particles. It is intended, in the next phase of this work, to use fluorescent seeding particles. These particles fluoresce light at a different wavelength than the laser light. A filter in front of the camera lens will therefore remove any laser light and only allow the illuminated seeding to be observed.

The current high speed camera was a Hitachi 16HM using standard 16mm film stock. Whilst this was found to be perfectly adequate it did require the development and digitisation of the film before analysis could be undertaken. This process was time consuming and, if a lot of images are recorded, expensive. The latest high speed video systems currently available on the market would increase the rate at which images could be acquired and digitised and, in the long term, could prove more cost effective.

Due to the transient nature of the flow it was found to be useful to animate the computed and experimental flow field to allow comparison. This paper may be accessed from the world wide web at http://www.strath.ac.uk/~clcs09/index.htm This page also includes animations of the bubble flows and vector maps.

6. CONCLUSIONS

This paper has shown that PIV, when combined with high speed photography, is capable of measuring transient flow fields.

7. REFERENCES

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