Hydrogen Bubble Seeding for Particle Image Velocimetry

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Flow visualization is an important element in the understanding of fluid flow phenomena, both for the analysis of new aerodynamic structures as well as for applications in education. Whilst there are many techniques for the qualitative visualization of flows the ability to quantitatively describe entire flow situations is much more complex. Particle image velocimetry (PIV) is one such quantitative technique; however its applicability is limited as it can be both expensive and dangerous for its requirement of high power lasers. This study aims to establish the potential for hydrogen bubbles generated from electrolysis as a seeding medium for general purpose water tunnel PIV flow analysis (termed bubble image velocimetry or BIV). Hydrogen bubbles generated in the upstream section of the water tank pass over a cylinder and images are taken of the seeded wake section. Captured images are analyzed using PIV software to construct vector field diagrams which are then compared to images created using high accuracy techniques for validation.

**Nomenclature**

- $Re$ = Reynolds number
- $D$ = cylinder diameter
- $V$ = free stream velocity
- $\rho$ = density of water
- $\mu$ = dynamic viscosity of water

I. Introduction

The capacity to visualize the fluid flow around objects has been important for applications and advancing understanding in fluid mechanics and aerodynamics for decades. For water tunnel testing, typical methods such as dye release, solid particles, droplets and the generation of hydrogen bubbles via electrolysis have been applied in research, development and education to understand the complex flow scenarios which can occur over structures.

Particle image velocimetry (PIV) is a technique which utilizes particle visualization to produce vector fields and hence gives the ability to extract quantitative data for the given flow scenario. A medium is released to seed the flow and a laser is used to illuminate a fixed sheet or plane to which a camera can focus. Two images are then taken at a time separation dependent on fluid flow speed and image correlation software is then used to track the movement of particles from one image to another. Given this information the velocity of the flow inside the complex field can be found across the entire area exposed to the two images. The characteristics of flow inside the complex field can thus be inferred. The result is a set of vectors representing the fluid flow velocity at discrete points, dependent on the size of the interrogation windows utilized in image analysis. The application of PIV however can be costly, as the laser required and the typical seeding particles employed can not only be expensive but potentially dangerous, which limits the usage of PIV to advanced research facilities and high level industry.

Hydrogen bubble release is an immensely versatile technique for qualitative complex flow visualization and does not require replacement of the testing medium (as do some other mediums such as dye release). A simple and inexpensive circuit can be utilized to generate a virtually endless supply of seeding and requires minimal knowledge to implement. Due to the inherent reflectivity of the bubbles, minimal lighting requirements are needed in order to

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be able to focus optical equipment and capture images of the flow with relatively high quality. The usefulness of hydrogen bubble visualization as a numerical analysis method is limited however, in that it does not provide quantitative information on the state of discrete points in a flow system and rather provides a general overview of the flow patterns.

A technique which can utilize the ease of hydrogen bubble production and external lighting, married with the interpretational abilities of PIV, would allow general purpose quantitative flow analysis to be performed safely, cost effectively and with much greater simplicity than current techniques. Using hydrogen bubbles as a seeding for particle image velocimetry (dubbed bubble image velocimetry or BIV) has some limitations for quantitative flow analysis which may decrease its accuracy when compared to PIV; including the buoyancy effects on the bubbles causing a net inherent upwards velocity and the possibility of the micro-flow around each bubble being disturbed due to this movement. This investigation aims to establish the potential for BIV to function as an analytical technique, to prove it can obtain a degree of accuracy which is acceptable for many general flow applications and to explore the limitations inherent in the technique itself.

II. Experimental Set Up

A. Water Channel Facility

The experiments were performed in a recirculating free surface water channel facility located in the Michell Laboratory at The University of Melbourne. The observational area in which the experiments were conducted is constructed of glass and has a cross sectional dimension of 0.5x0.5m and an overall length of 1.1m. The roof of the observation area is open to allow the placement and manipulation of test models within the channel. This area is located downstream of a contraction in the tunnel from the pumping section of the water channel so that the free stream velocity is steady. The cylindrical model was placed 0.65m from the upstream entrance to the observational area.

![Figure 1. Schematic of water channel facility](image)

B. Hydrogen Bubble Generation

Hydrogen bubbles were generated through the process of electrolysis. A platinum iridium wire 50µm in diameter and of length 0.55m was submerged to serve as the cathode of a DC circuit. This wire was connected to a 0.1x0.1m galvanized steel mesh, acting as the anode, via a power supply in order to form an electrolytic cell. With the anode submerged at a distance of 0.1m from the cathode, a potential difference of 150 volts at 0.28 amps was applied. Hydrogen and oxygen gas were liberated at the cathode and anode respectively following the equation:

$$2H_2O(l) = 2H_2(g) + O_2(g)$$

Due to the consistent flow velocity from the water tunnel hydrogen bubbles were swept into the flow after forming on the wire cathode to produce a planar sheet of fine bubbles. This procedure produced bubbles of average diameter 320µm which were utilized in all subsequent experiments. As the bubbles are formed their natural tendency is to move vertically upwards due to their buoyancy in the low velocity region in the wake of the wire.
When this occurs the bubbles are liable to coalesce and form larger bubbles which become less useful for analysis due to their greater buoyancy. To reduce these effects the wire cathode was offset at an angle of 65° to the upstream horizontal direction so that as the bubbles raised no bubble interaction would occur (Figure 2). In order that the wake of the wire did not affect the pathline of the individual bubbles being generated, a distance of 0.15m was allowed between the cathode and model such that the effects of this wake have sufficient time to decay. This also allows for the bubble sheet to acquire the velocity of the free stream flow so that the bubbles give a true representation of the flow around the model.[1]

C. Testing Procedure
The test model utilized was a cylinder of diameter 0.034m which was positioned via interference fitting into the observational area of the water channel. The water tunnel operated at a free stream velocity of 0.12m/s which, with a hydro-dynamically smooth surface, yields a Reynolds number of $Re = 4080$, where

$$Re = \frac{\rho V D}{\mu}$$

The water tunnel and model arrangement can be seen in Figure 2. Two 1000 Watt halogen flood lights, angled at 10° to the vertical plane, were placed above and below the water channel to illuminate the bubble sheet. Ambient lighting was minimized by covering all nonessential clear glass viewports to the observation area of the water channel. An IDT Y3 Classic CMOS camera with 1.3 megapixel resolution was used to capture the required images. The camera was aligned perpendicular to the plane of the bubbles at a distance of 0.6m from the water channel sides. The focus was adjusted such that the downstream half of the cylinder occupied the central left region of the frame, with the image extending 0.22m (approximately 6.5 cylinder diameters) downstream to capture the region of interest in the shedding wake. A sampling frequency of 200Hz was utilized over a 12.5 second time period at an exposure time of 439µs per image, resulting in a total of 2500 images. This set up allowed for images to be gathered covering approximately 10 shedding periods of the wake. This was suitable for the preliminary study documented here however for detailed study many more periods would be required to yield statistically accurate results.

Additional calibration images were also captured in order to determine a scaling factor for a pixel to meter conversion necessary to calculate both the bubble diameter and inherent net upward velocity due to buoyancy.

![Figure 2 Schematic diagram of experimental set up](image)

III. Analysis
The transformation of the qualitative images to a quantitative tool is accomplished through image pair processing. Initially the images are contrast adjusted to yield high distinction between the hydrogen bubble seeds and the background (Figure 3). Sequential pairs of images are then compared by quantifying image data within a defined interrogation window which is then correlated with the matching window in the second image. A vector is constructed by comparing the two dimensional relative translation between the correlated pairs, and when conducted over multiple interrogation sets allows for the construction of a vector field diagram across the entire image.
The open source software PIVlab was used to process 2500 images in alternating image pair sets (e.g., 1-2, 3-4...). The algorithm used was the direct correlation method with a 64x64 pixel interrogation window size and a 50% overlap. Given the 1280x1024 pixel resolution used, the resulting generated vector fields consisted of 38x39 vectors corresponding to each interrogation window, with a set of vectors specifying the x and y coordinates, as well as horizontal and vertical components of velocity for each. Data sets were converted from pixels/frame to meters/second by analyzing a calibration image which contained a known dimension and determining a conversion ratio which also accounted for image sampling frequency. The final data was normalized so that the velocities are given in terms of ratios of the free stream velocity and distances are given in cylinder diameters.

The calibration images were analyzed in a similar manner and the mean velocity in the vertical direction was determined, corresponding to the inherent buoyancy of the hydrogen bubbles. By averaging this data over the entire flow field, a mean vertical velocity due to buoyancy was determined. This buoyancy velocity could then be subtracted from the experimental results to remove the net vertical skew. In this instance, it was found that the vertical component of velocity due to buoyancy was 5% of the free stream velocity, and hence was deemed negligible within experimental error.

![Figure 3. Contrast adjusted hydrogen bubbles](image)

Contrast adjustment allows for the distinct separation of bubbles from background and makes bubble size calculation possible.

For validation of results, a numerically generated series of images were created. The analytical techniques applied in this numerical simulation involve the time-integration of the three-dimensional incompressible Navier-Stokes and continuity equations. The method essentially solves filtered Navier-Stokes equations with a sub grid scale model of the eddy viscosity type. A slice from the center of the three-dimensional region was used to produce the comparison images. Figure 4 shows the computational domain of the simulation. A cylinder of 0.027m diameter was used as the model and the inlet velocity varied to achieve a Reynolds number of 3900. [2]

![Figure 4. Schematic of numerical simulation domain](image)
IV. Results

After the initial image analysis has been conducted the resulting data can be manipulated in a variety of ways to gain various interpretations of the raw data. An instantaneous velocity vector field of the wake behind the cylinder can be constructed for any sequential image pair throughout the entire series which clearly displays the flow patterns including the vortices present at that particular instant (Figure 5). It is evident that by using BIV a more complete understanding of the complex fluid phenomena in the wake region can be obtained when compared to a strictly qualitative visual inspection.

To validate the accuracy of the BIV analysis, further comparison of the instantaneous velocity vector field can be made against a similar field produced computationally. Figure 6 shows such a comparison. It is clear that BIV is able to capture much of the general characteristics of the numerical model with a region of low velocity directly behind the cylinder which increases in magnitude with the downstream direction. Individual vortices are well defined exhibiting the expected Karman vortex street pattern.

By averaging the wake profile at each interrogation window over the entire range of captured data, a time averaged wake profile of the cylinder can be obtained over the ten shedding periods (Figure 7). This image clearly shows a dark region of lowest magnitude directly behind the cylinder, which was to be expected due to recirculation occurring within this region. Another characteristic of note is the longevity of the low averaged velocity region which persists for approximately 3-3.5 cylinder diameters. In the center of the immediate wake is a higher velocity magnitude area which penetrates into the low velocity region which is faithfully replicated by BIV. In general, the patterns above and below the direct wake are also consistent. The similarity of the time averaged BIV data to that obtained through numerical methods shows that the BIV analysis is reproducing the wake profile of the cylinder without bias, which would become statistically evident in the data as a skew in the wake to a particular direction.

Figure 5. Velocity vector field from BIV (right) resulting from analysis of hydrogen bubble seeded image (left). It is evident the general characteristics of the flow are much more recognizable in vector form.

Figure 6. Comparison of BIV data (left) against numerical simulation (right) for instantaneous magnitudes. Note the similarity in shedding pattern and the general increasing velocity with downstream direction.
Note that both sets of data feature a region of low velocity in the immediate wake which dissipates downstream. In addition, the regions above and below the wake exhibit similar patterns.

Figure 8. The RMS wake signatures from BIV (left) and computer simulation (right). Both sets of data display a distinct cone of variability in line with the expected vortex shedding region.

Another useful set of data to compare is the RMS values of the horizontal components of velocity. RMS values are representative of the time dependent changes from the mean velocity rather than a net mean. In this way a comparison will give evidence as to the strength of BIV in depicting vortex components as they travel in the wake section. Figure 8 shows the BIV calculated RMS wake signature in contrast with that produced from computer simulation. It is immediately evident that the variability occurs within a cone region behind the cylinder, where vortex shedding is occurring. The data from BIV accurately reflects this trend indicating that it is capable of detecting vortex structures and their inherent velocity variability at the correct locations.

V. Conclusion

An introductory study has been conducted into the potential for hydrogen bubbles to act as a seeding medium for image velocimetry. The images obtained and subsequent analysis provided strong evidence to suggest the level of accuracy obtained using hydrogen bubbles is sufficient for complex flow analysis. Comparisons of the resulting hydrogen bubble vector fields to computer simulations have illustrated the reasonable level of accuracy that can be obtained.

Using hydrogen bubbles as a seeding medium for BIV has multiple benefits over conventional PIV techniques. The requirement for lasers, complex seeding mechanisms and the inherent costs and hazards involved are virtually eliminated and the end user skill requirement is dramatically reduced. In addition, the impermanence of hydrogen bubbles eliminates the need to clean or filter the flow medium after use. It is recognized that the accuracy achievable through BIV may not be suited to certain applications in which PIV would be more appropriate, however for many purposes this deficit in accuracy is offset by the simplicity of implementation. Many institutions already make use of qualitative flow visualization techniques using hydrogen bubbles hence the application of BIV represents a minimal time and cost investment over existing techniques, yet yields a significant increase in usable experimental data.

Future studies into the applicability of BIV would need to consider the difficulties in maintaining seed density in trailing wake regions, particularly where strong backflow and vortices may create a barrier to seed penetration. An array of Reynolds numbers should be considered and studied for the relative effectiveness of the technique for varying applications, taking into consideration the limitations of bubble generation at various free stream velocities. In addition, considerations to counter the influence of bubble buoyancy should be explored in order that the accuracy of the technique may be further increased.
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