Full-Volume, Three-Dimensional, Transient Measurements of Bubbly Flows Using Particle Tracking Velocimetry and Shadow Image Velocimetry Coupled with Pattern Recognition Techniques

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Final Report

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This is the third phase report of the present NEER project. The overall goal, as described in the initial report (report for phase 1), was to develop a state-of-the-art; non-intrusive diagnostic tool to perform simultaneous measurements of both the temporal and three-dimensional spatial velocity of the two phases of a bubbly flow. These measurements are required to provide a foundation for studying the constitutive closure relations needed in computational fluid dynamics and best-estimate thermal hydraulic codes employed in nuclear reactor safety analysis and severe accident simulation. Such kinds of full-field measurements are not achievable through the commonly used point-measurement techniques, such as hot wire, conductance probe, laser Doppler anemometry, etc. The results can also be used in several other applications, such as the dynamic transport of pollutants in water or studies of the dispersion of hazardous waste.

A hybrid of the stereoscopic Particle Tracking Velocimetry (PTV) and the Shadow Image Velocimetry (SIV) flow measurement techniques was developed to provide three-dimensional full-volume and transient velocity fields of the phases of a bubbly flow. This hybrid flow measurement technique was applied to provide us with the shape and trajectory of a single air bubble rising in stagnant water, in a restricted medium.

Pattern recognition algorithms were used to track the seed tracers embedded in the flow. These algorithms were proven to accurately describe the flow field in regions of low and high velocity gradients. Two tracking were used: an Architecture Resonance Theory 2 Neural Network (ART2 NN) and the Spring Model (SM). The ART2 NN tracks tracer particles during four consecutive frames, so it provides not only the velocity vector, but also the acceleration in a Lagrangian reference frame. For regions of high velocity gradient, the SM was able to accurately track the tracer particles within two consecutive frames. These two pattern recognition-based algorithms were applied independently to the flow images. By combining the information from both tracking techniques, the full-volume, three-dimensional velocity field was determined. The ART2 NN provided information of regions surrounding the rising bubble, while the SM described the flow in the bubble wake. The developed imaging and pattern recognition techniques used for this study can also be applied to medical imaging.

In the Phase I report, a description of the constructed test facility was presented. The camera calibration technique and a method to reduce refraction problems were developed and presented. In addition, the PTV and SIV flow measurement techniques and tracking routines the ART2 NN and the SM were described and validated. During Phase II, the bubble shape and trajectory of the dispersed phase were obtained utilizing the developed state-of-the-art SIV technique. The wall influence on the shape and motion of the bubble was investigated. The magnitude and coefficients of the drag and lift forces acting on the bubble were also inferred from the information of the SIV and PTV techniques. In addition, the transient behavior of the total and turbulent kinetic energy in the test volume was presented. Results about the pseudo-turbulence generated by a rising bubble were introduced and discussed. Reynolds stresses were calculated. The structure of the bubble wake was delineated, and the influence of the bubble on the flow field was also determined. These experimental data can be used to understand the evolution and the complex phenomena of turbulent bubbly flows.

In Phase III, the single bubble dynamics study performed and presented in Phase II report was extended to a dilute bubbly flow investigation. The developed and validated PTV and SIV techniques were also improved for this task. New equipment was acquired to increase the resolution of the measurements. A test facility for studying bubbly flows with a wide range of Reynolds numbers was constructed. The test facility and experimental setup are shown. The experimental conditions are described, and sample images of a two-phase turbulent bubbly flow are shown in figures 1-5. A proposed data analysis methodology is presented in figures 6 and 7. The obtained experimental data can be used to validate the turbulence models utilized in computational fluid dynamics and best-estimate thermal hydraulic codes.

PHASE III

Objective: The first objective of phase III was to construct a test facility to perform turbulent bubbly flow PIV three-dimensional measurements.

Accomplishments: A schematic of the flow and Particle Image Velocimetry (PIV) systems is shown in figure 1. The illumination source is a Twin Nd:YAG laser. Each of the laser rods fires at a frequency of 30 Hz. The laser delivers about 350 mJ per pulse, at a wavelength of 532 nm. The pulse width is about 7 ns. The two-dimensional liquid velocity fields are acquired by a 1016 × 1016 pixel high resolution CCD camera. The camera runs at 30 Hz in continuous mode, but it has the triggered double exposure capability, which allows for studying high velocity fields. In the triggered double exposure mode, the camera can acquire 60 frames per second at full resolution, under certain conditions.

Two medium resolution CCD cameras, here referred as to shadow cameras A and B respectively, are employed to study the dispersed phase. These cameras have a resolution of 640 × 480 pixel at 30 Hz. The SIV technique is used to track the bubbles and determine bubbles' shapes. The illumination sources are red LED panels. These panels use high luminance single LEDs, and are home made. A schematic of the camera system arrangement is shown in figure 2. The shadow cameras are in a perpendicular position, respect to each other, so three-dimensional reconstruction of the bubble motion and shape are possible, as done with the single rising bubble in Phase II.

The images acquired by the cameras are sent to high performance imaging boards, and then to the RAM of personal computers. The laser, CCD cameras and LEDs system is synchronized by a high accuracy pulse generator. The software required to run the experiments is in the LABVIEW environment, and home developed.
The flow facility allows to study bubbly flows from stagnant water to turbulent Reynolds number of about 21000. The volumetric quality ranges from 0 to 7.4%. The bubble size can be controlled by varying the water flow inlet through the bubble generator, as it can be seen in figure 1. Pictures of the experimental setup before and during laser illumination and image acquisition are shown in figure 3. Example PIV images without and after image enhancement can be seen in figure 4. The simultaneous images acquired by the shadow cameras are shown in figure 5.

Objective: Develop a methodology to analyze the PIV and SIV images.
Accomplishments: the proposed methodology for data analysis from PIV and SIV images are shown in figures 6 and 7, respectively..

Other Accomplishments: Two Ph.D. Dissertations we completed under partial support of this project. Details of the project can be found in these two Dissertations.

- Schmidl, William Daniel 1999 Three-Dimensional Experimental Investigation of the Two-Phase Flow Structure in a Bubbly Pipe Flow. Ph.D. Dissertation. Texas A&M University, College Station, TX.
- Ortiz-Villafuerte, Javier 1999 Three-Dimensional Experimental Investigation of the Shape and Dynamics of a Rising Bubble in Stagnant Water with Particle Tracking Velocimetry. Ph.D. Dissertation. Texas A&M University, College Station, TX.

Since most of the results obtained during this project come from second Dissertation, this has been attached to this final report.

In addition, several papers were presented and published during the project.

REFEREED JOURNAL PUBLICATIONS

1. Hassan, Yassin A.; Ortiz-Villafuerte, Javier & Todd, Donald R. 2001, "Velocity Measurements in Bubbly Flows with Particle Tracking Velocimetry," *Flow Visualization& Processing,* Vol. **8**, pp. 243-252, 2001.

2. To appear in special issue of *Journal of Flow Visualization & Image Processing.*

3. Ortiz-Villafuerte, Javier; Hassan, Yassin A. & Schmidl, William D. 2001 Rocking Motion, Trajectory and Shape of Bubbles Rising in Small Diameter Pipes," *Experimental Thermal and Fluid Science* **25** 1-2, 43-53.

4. Hassan, Yassin A.; Ortiz-Villafuerte, Javier & Schmidl, William D. 2001, " Three-Dimensional Measurements of Single Bubble Dynamics in a Small Diameter Pipe Using Stereoscopic Particle Image Velocimetry, " *International Journal of Multiphase Flow* **27** 5, 817-842.

5. Ortiz-Villafuerte, Javier; Hassan, Yassin A. & Schmidl, William D. 2000, "Three-Dimensional PTV Study of the Surrounding Flow and Wake of a Bubble Rising in a Stagnant Liquid," *Experiments in Fluids* **29** 7, S202-S210.

6. Hassan, Yassin A.; Schmidl, William D. & Ortiz-Villafuerte, Javier 1999, " Three-Dimensional Bubbly Flow Measurement Using PIV," *Journal of Visualization* **1** 3, 291-301.

OTHER REFEREED PUBLICATIONS (transactions, workshops, conferences)

1. Ortiz-Villafuerte, Javier; Hassan, Yassin A.; Schmidl, William D.; Sánchez-Silva, Florencio; Todd, Donald R. & Yilmaz, Fatma 2001 Three-Dimensional Turbulence Measurements in Bubbly Two-Phase Flows with Particle Image Velocimetry. *4th International Conference on Multiphase Flow (ICMF-2001)*, New Orleans, LA, U.S.A., May 27 - June 1, **534**.

2. Todd, Donald R.; Ortiz-Villafuerte, Javier; Schmidl, William D.; Hassan, Yassin A. & Sánchez-Silva, Florencio 2001 Analysis of Bubbly Flow Using Particle Image Velocimetry. *Ninth International Conference on Nuclear Engineering (ICONE-9)*, Nice, France, April 8-12, **ICONE-766**.

3. Ortiz-Villafuerte, Javier; Todd, Donald R.; Schmidl, William D. & Hassan, Yassin A. 2000 Turbulence Measurements in Bubbly Two-Phase Flows with Particle Image Velocimetry. *ANS Winter Meeting*, Washington, DC, U.S.A., November 12-16, ANS Transactions, 380-381.

4. Ortiz-Villafuerte, Javier; Schmidl, William D. & Hassan, Yassin A. 2000 Three-Dimensional Stereo Measurements in Bubbly Pipe Flows with Particle Image Velocimetry. *International Mechanical Engineering Congress & Exposition (IMECE'00)*, Orlando, FL, U.S.A., November 5-10.

5. Todd, Donald R.; Hassan, Yassin A. & Ortiz-Villafuerte, Javier 2000 Flow Visualization in Bubbly Flow Regimes Using Particle Tracking Velocimetry. *9th International Symposium on Flow Visualization (9ISFV)*, Edinburgh, Scotland, U.K., August 22-25, **390**.

6. Ortiz-Villafuerte, Javier; Schmidl, William D. & Hassan, Yassin A. 2000 Particle Tracking Velocimetry Measurements of the Flow Field Generated by a Rising Bubble in a Small Diameter Pipe. *ASME Fluids Engineering Division Summer Meeting (FEDSM'00)*, Boston, MA, U.S.A., June 11-15, **FEDSM2000-11322**.

7. Ortiz-Villafuerte, Javier; Schmidl, William D. & Hassan, Yassin A. 2000 Three-Dimensional Study of Single Bubble Dynamics and the Surrounding Flow Field in a Small Diameter Pipe by Using Particle Tracking Velocimetry. *8th International Conference on Nuclear Engineering (ICONE-8)*, Baltimore, MD, U.S.A., April 2-6, **ICONE-8635**.

8. Ortiz-Villafuerte, Javier; Schmidl, William D. & Hassan, Yassin A. 1999 Experimental Study of the Transient Turbulence generated by a Bubble Using PIV. *International Mechanical Engineering Congress and Exposition (IMECE'99)*, Nashville, TN, U.S.A., November 14-19, Proceedings of the ASME **HTD 364-4**, 297-304.

9. Ortiz-Villafuerte, Javier; Hassan, Yassin A. & Schmidl, William D. 1999 Study of the Bubble Shape Using the PIV Shadow Technique. *ANS Winter Meeting*, Long Beach, CA, U.S.A., November 14-18, ANS Transactions **81**, 344-347.

10. Hassan, Yassin A.; Ortiz-Villafuerte, Javier & Schmidl, William D. 1999 Three-Dimensional Bubbly Flow Measurements Using Stereoscopic Particle Image Velocimetry. *Ninth International Topical Meeting on Nuclear Thermal-Hydraulics (NURETH-9)*, San Francisco, CA, U.S.A., October 3-8.

11. Ortiz-Villafuerte, Javier; Schmidl, William D. & Hassan, Yassin A. 1999 Three-Dimensional PTV Experimental Study of the Wake of a Bubble Rising in a Liquid. *Third International Workshop on Particle Image Velocimetry (PIV'99)*, Santa Barbara, CA, U.S.A., September.

12. Hassan, Yassin A.; Schmidl, William D.; Ortiz-Villafuerte, Javier & Scharf, Jordan R. 1999 Analysis of the Three-Dimensional Structure of a Bubble Wake Using PIV and Galilean Decomposition. *33rd National Heat Transfer Conference (NHTC'99)*, Albuquerque, NM, U.S.A., August 15-17, **NHTC99-308**.

13. Hassan, Yassin A.; Schmidl, William D.; Ortiz-Villafuerte, Javier & Scharf, Jordan R. 1999 Stereoscopic PIV Study of a Rising Bubble in Stagnant Liquid. *3rd ASME/JSME Joint Fluids Engineering Conference (FEDSM99)*, San Francisco, CA, U.S.A., July 18-22, **FEDSM99-7266.**

14. Ortiz-Villafuerte, Javier; Schmidl, William D. & Hassan, Yassin A. 1999 Three-Dimensional Experimental Study of the Wake of a Bubble Rising in Stagnant Liquid. *ANS Annual Meeting*, Boston, MA, U.S.A., June 6-10, ANS Transactions **80**, 302-305.

15. Hassan, Yassin A.; Ortiz-Villafuerte, Javier & Schmidl, William D. 1999 Dynamics of the Wake of a Rising Single Bubble in Stagnant Liquid. *Two-Phase Flow Modeling and Experimentation 1999 Vol. 2.* Editors: Celata, G. P.; Di Marco, P. & Shah, R. K. Edizioni ETS, Pisa, Italy, 1079-1084.

16. Hassan, Yassin A.; Ortiz-Villafuerte, Javier; Schmidl, William D. & Scharf, Jordan R. 1999 Measurements of a Rising Single Bubble in Stagnant Liquid. *2nd Pacific Symposium on Flow Visualization and Image Processing (PSFVIP-2)*, Honolulu, HW, U.S.A., May 16-19, **PF156.**

17. Ortiz-Villafuerte, Javier; Hassan, Yassin A. & Schmidl, William D 1998 Bubble Shape Identification Using Shadow Particle Image Velocimetry Technique. *ANS Winter Meeting*, Washington, DC, U.S.A., November 15-19, ANS Transactions **79**, 357-360.

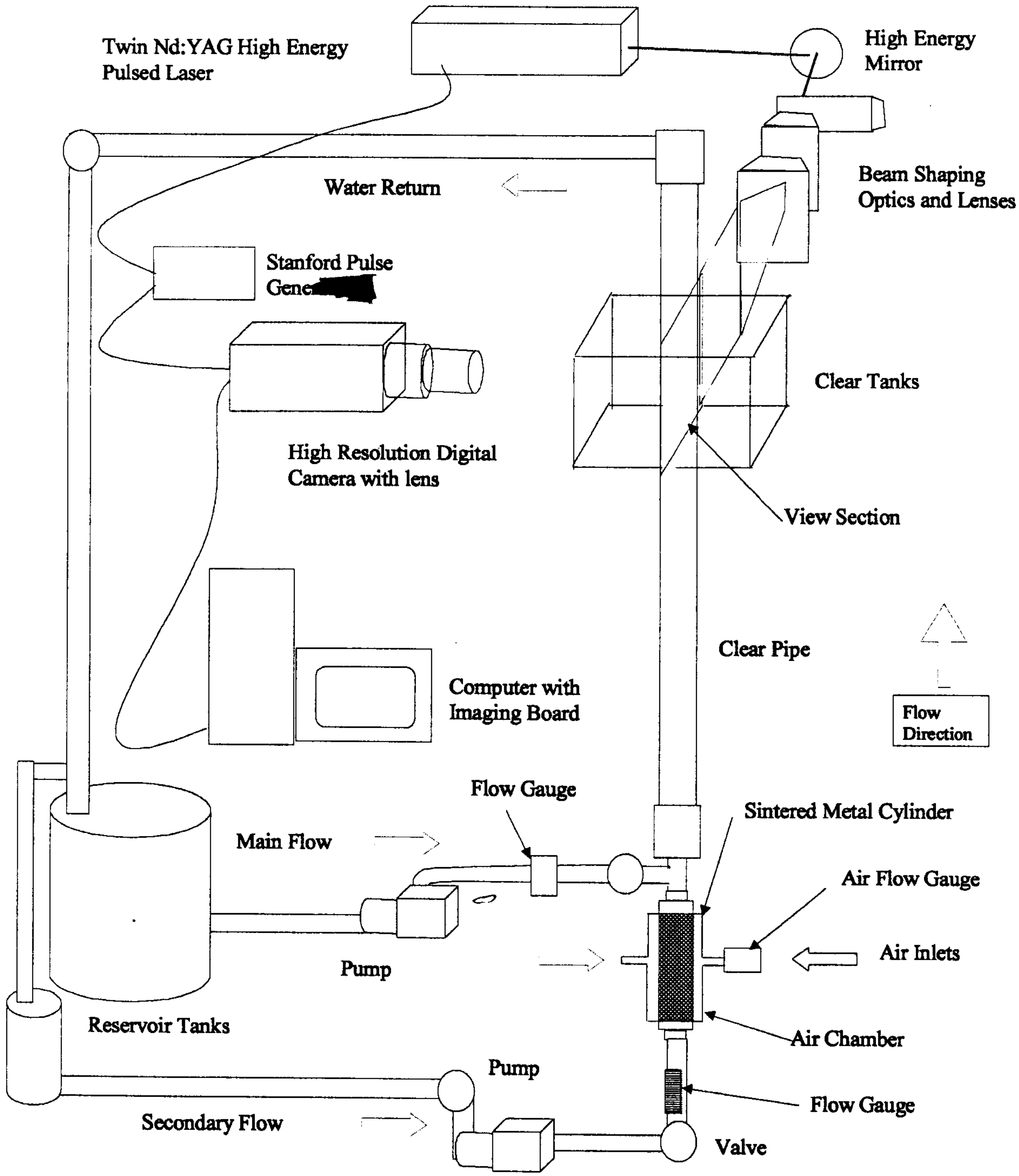


Figure 1. Schematic of the flow and PIV systems.

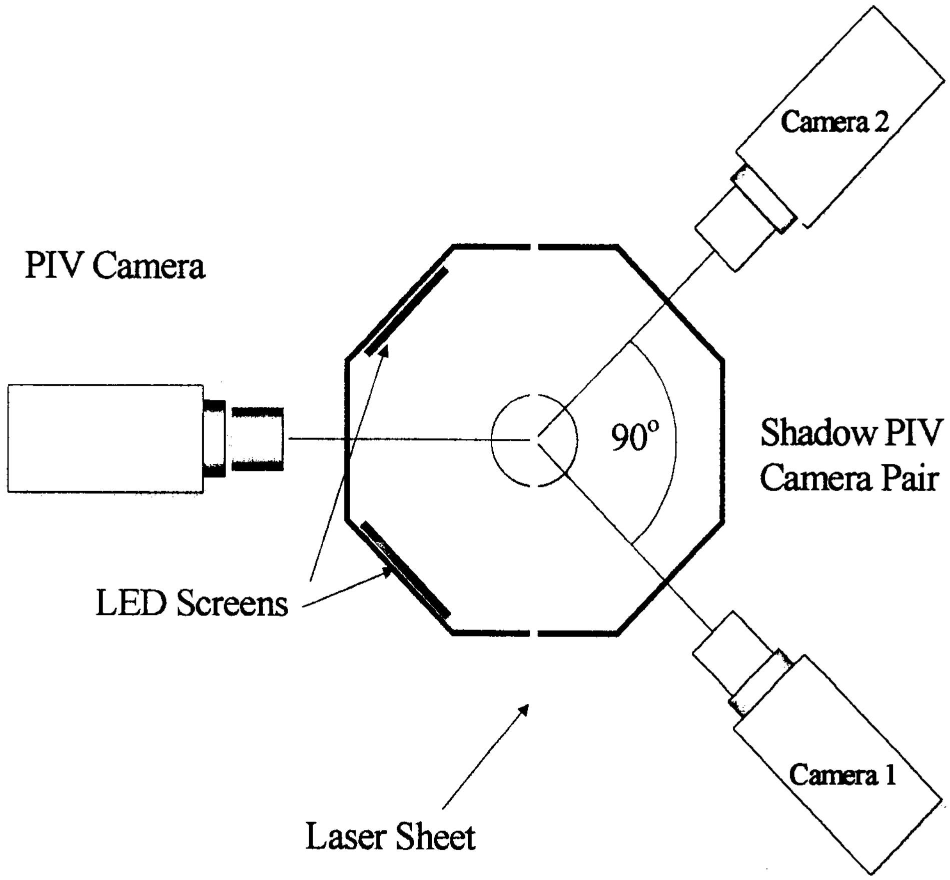
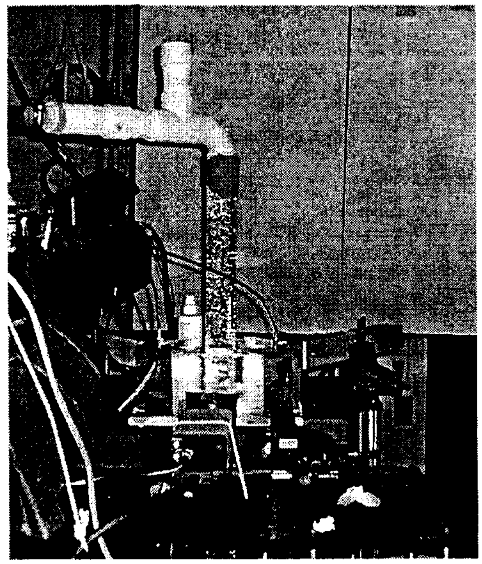
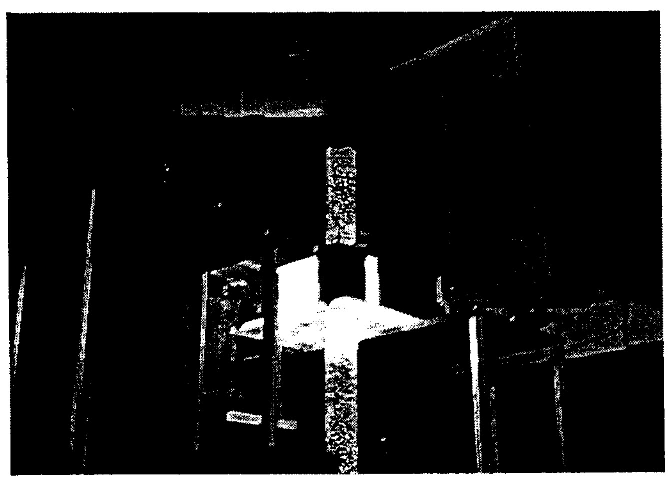


Figure 2. Schematic of the camera system arrangement.



(a)



(b)

Figure 3. Experimental setup. a) Before data acquisition. b) During data acquisition.

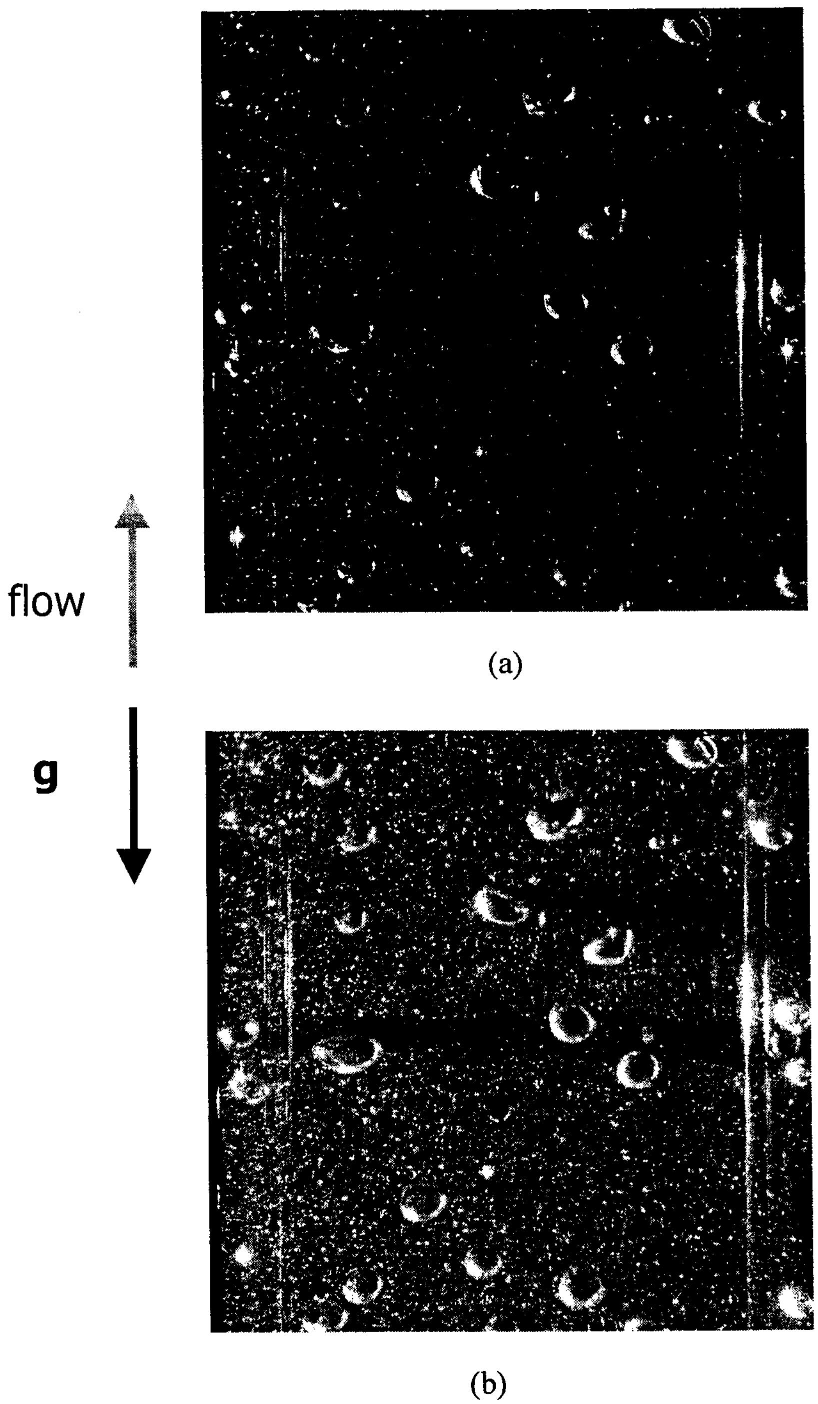


Figure 4. Typical PIV images. a) Original. b) Enhanced.

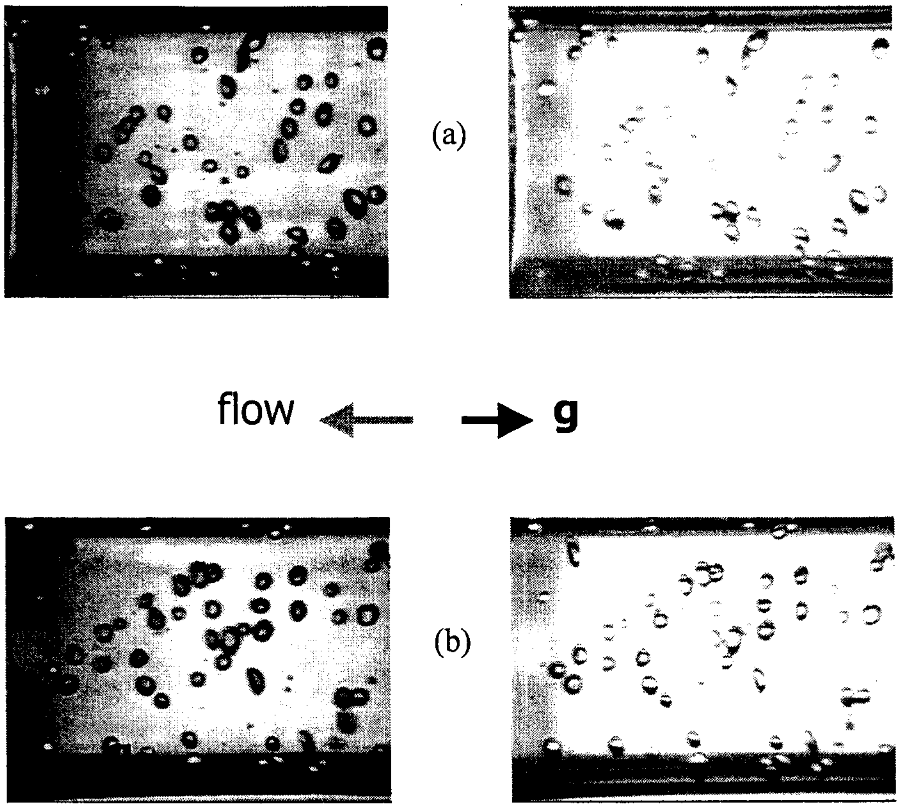


Figure 5. Typical SIV images. Original and enhanced sahdow images.
a) Images from shadow camera A. b) Images from shadow camera B.

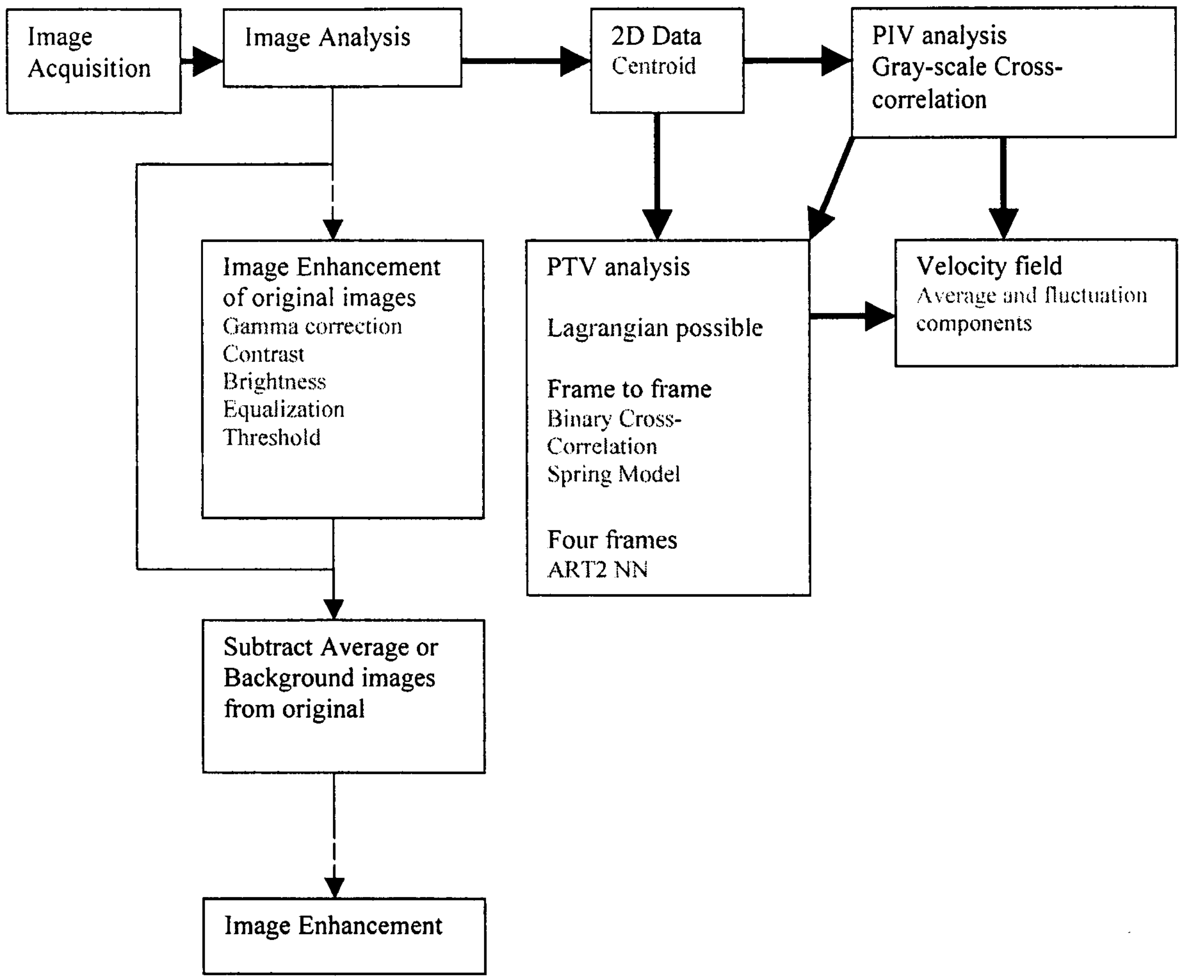


Figure 6. Methodology for PIV data analysis.

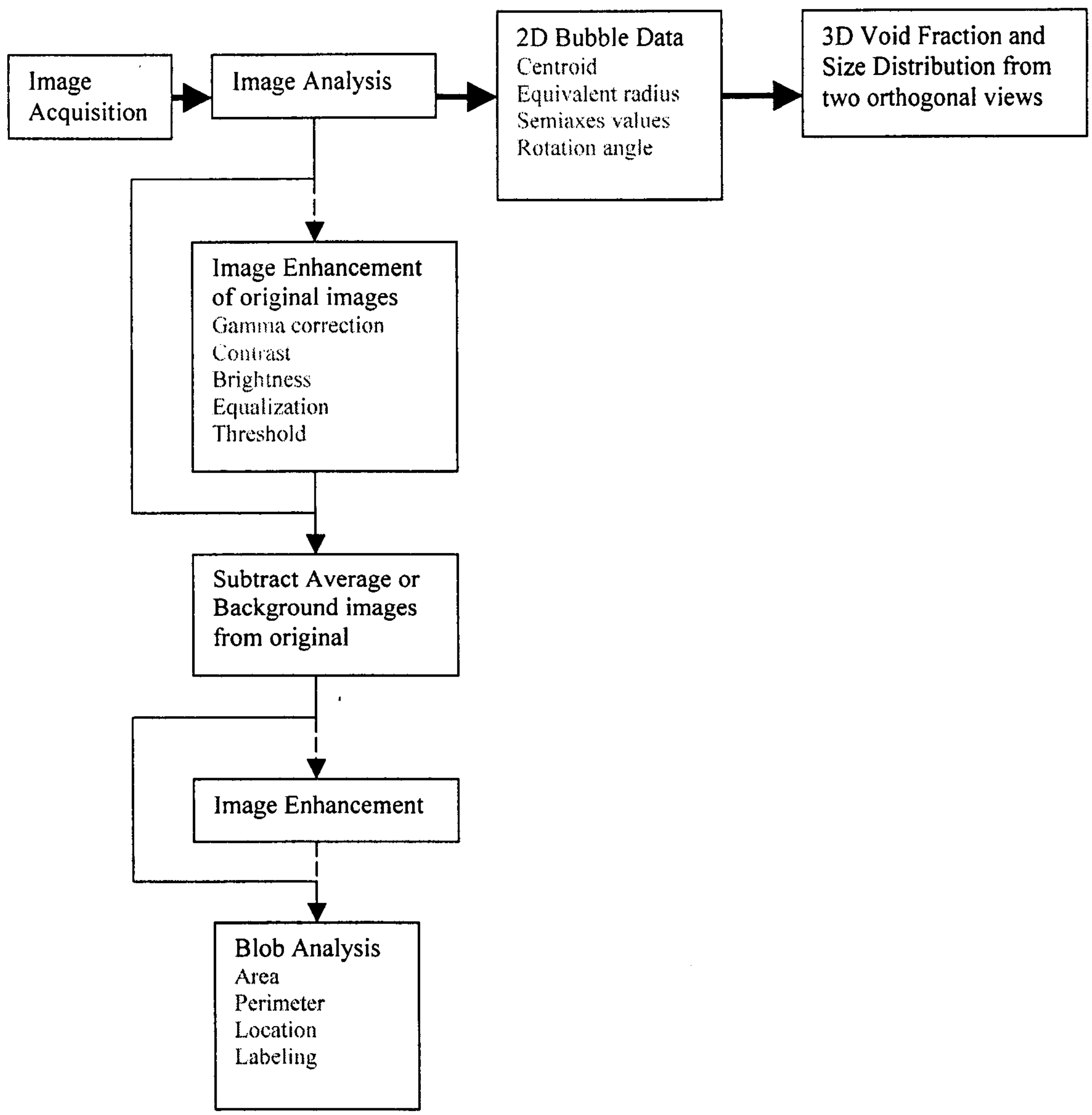


Figure 7. Methodology for SIV data analysis.