TRANSIENT THREE-DIMENSIONAL EXPERIMENTAL INVESTIGATION OF THE SHAPE AND DYNAMICS OF AN AIR BUBBLE IN STAGNANT WATER IN A SMALL DIAMETER PIPE WITH PARTICLE TRACKING VELOCIMETRY

A Dissertation

by

JAVIER ORTIZ VILLAFUERTE

Submitted to Texas A&M University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Major Subject: Nuclear Engineering

TABLE OF CONTENTS

Page

ABSTRACT iii

DEDICATION v

ACKNOWLEDGMENTS vi

TABLE OF CONTENTS vii

LIST OF FIGURES ix

LIST OF TABLES xiii

CHAPTER

I INTRODUCTION 1

1.1 Bubbly flow studies 2
1.2 Single bubble dynamics 3
1.3 Bubble shape analysis and three-dimensional reconstruction 5
1.4 Three-dimensional particle image velocimetry and tracking algorithms . 7
1.5 Objectives 9

II EXPERIMENTAL SETUP AND CAMERA CALIBRATION 11

2.1 Experimental setup 11
2.2 Camera calibration 14
2.2.1 The pinhole camera model and the direct linear transformation method 15
2.2.2 Calibration data 17
2.2.3 Computation of transformation coefficients 19
2.2.4 Calibration error 21

III HYBRID PARTICLE TRACKING VELOCIMETRY AND THREE-DIMENSIONAL VELOCITY FIELD RECONSTRUCTION 24

3.1 Pulsed-light velocimetry 24
3.2 Particle image velocimetry 25
3.3 Hybrid particle tracking technique 26
3.4 Matching of velocity vectors from stereo images 28
3.5 Determination of the three-dimensional position of the tracer particles .. 32

IV BUBBLE SHAPE IDENTIFICATION AND RECONSTRUCTION 34

4.1 Bubble detection in a bubbly flow 35
4.2 The shadow particle image velocimetry flow visualization technique 36
4.3 Two-dimensional bubble shape reconstruction 37
4.3.1 The dynamic generalized Hough transform algorithm 41

CHAPTER Page

4.3.2 Accuracy of the reconstruction 42
4.4 Three-dimensional bubble shape reconstruction 45

V FLOW AROUND A RISING BUBBLE AND WITHIN ITS WAKE 49

5.1 Uncertainty analysis of PIV measurements and error propagation 49
5.1.1 The Stokes number 50
5.1.2 Accuracy of two-dimensional localization of particle centroid 50
5.1.3 Uncertainty of three-dimensional particle position and instantaneous velocity 51
5.1.4 Error propagation 51
5.2 Theoretical background 53
5.3 Nodalization and conditional sampling 57
5.4 Mean flow field description 62
5.5 Turbulent flow field description 72
5.6 Transient analysis of the kinetic energy 77

VI SHAPE, TRAJECTORY AND FORCES ACTING ON A BUBBLE RISING IN A SMALL DIAMETER PIPE 86

6.1 Theoretical background 86
6.1.1 Bubble shape 87
6.1.2 The equation of motion 88
6.1.3 Nature of the forces acting on the bubble 89
6.2 Accuracy of measurements 92
6.3 Experimental results and discussion 94
6.3.1 Bubble shape and velocity analysis 94
6.3.2 Drag and lift forces acting on the bubble 100

VII CONCLUSIONS 112

REFERENCES 118

VITA 126

LIST OF FIGURES

FIGURE Page

1 a) Facility setup and camera configuration; and b) some relevant dimensions are shown. 12

2 Camera assembly 14

3 The pinhole camera. A point P in the 3D world coordinate system is projected into an image point I, located at the interception of the line joining the point P and the camera center of projection C through the camera image plane Π 15

4 The four simultaneous images of the calibration grid, when placed at the origin of the coordinate system. (a) Image from the Center camera; (b) image from the Left camera; (c) image from the Right camera; and (d) image from the Shadow camera 20

5 General process to determine the three-dimensional flow field. 27

6 The variation of u for the PIV cameras against its world position, x, at $y = 0$. Also shown the results of application of a linear regression to the data points. See text for notation. 29

7 The variation of u respect to the depth, y, at different x positions. a) Data from the Right Camera; and b) data from the Left Camera. Also shown, the results of applying a linear regression to the data points. 31

8 3D stereoscopic reconstruction technique. 33

9 Typical simultaneous images acquired by the PIV and Shadow cameras when the bubble is present in the test volume. a) Image from the Center camera. It shows the XZ world plane; and b) image from the Shadow camera. It shows the YZ world plane. These two images allow for the three-dimensional reconstruction of the bubble shape. 36

10 Bubble identification and reconstruction process for figure 9a. a) Binary image after applying the threshold and inversion operator; b) resulting image after applying size and salt-and-pepper operators to a; c) application of edge-detection operator to b; d) connectivity points to be used in the DGHT algorithm; e) the ellipse that best fits the connectivity points in d; and f) overlay of e and the original image. Also shown, the rotation angle with respect to the z-axis. 39

FIGURE Page

11 Bubble identification and reconstruction process for figure 9b. a) Binary image after applying the threshold and inversion operator; b) resulting image of applying size and salt-and-pepper operators to a; c) application of edge-detection operator to b; d) connectivity points to be used in the DGHT algorithm; e) the ellipse that best fits the connectivity points in d; and f) overlay of e and the original image. Also shown, the rotation angle with respect to the z-axis. 40

12 Histograms of three of the parameters of the ellipse that best fits the bubble in figure 9a, computed through the DGHT. a) Rotation angle; b) center of the ellipse on the x-direction; and c) value of the semiaxis on the x-direction. 43

13 Histograms of three of the parameters of the ellipse that best fits the bubble in figure 9b, computed through the DGHT. a) Rotation angle; b) center of the ellipse on the x-direction; and c) value of the semiaxis on the x-direction. 44

14 Calibration curves for computing world coordinates from image coordinates. a) Variation of y against u on images from the Shadow camera; and b) variation of z against v for images from both the Shadow and the Center cameras. 46

15 Three different views of the three-dimensional reconstruction of the bubble shown in figure 9, after combining information from the two-dimensional reconstructions shown in figures 10e and 11e. 48

16 Projection of the distribution of the bubble centroids for the experiment of 240 images on the XY plane. The anisotropy of the bubble paths during rising within the test volume should be noted. The bubbles were released at the pipe center. 58

17 Nodalization of the test section. (a) Gas; and (b) liquid phases. For the air bubble, the nodalization has been created considering an average equivalent bubble diameter of 3 mm, and its location is determined by its centroid. 58

18 Example of bubble trajectory at the center of the pipe. The two-dimensional projections of the trajectory from the Center and Shadow cameras, and the three-dimensional bubble reconstructions are shown. Actual trajectory is 1112. 60

19 Example of bubble trajectory along the pipe wall. The two-dimensional projections of the trajectory from the Center and Shadow cameras, and the three-dimensional bubble reconstructions are shown. Actual trajectory is 4445. 61

FIGURE Page

20 Total number of vectors used for the averaging operation at each time step for both bubble trajectories. $t = 0$ is the first frame in which the bubble appears in the viewing volume. 62

21 Distribution of a) mean kinetic energy, in μJ; and b) vorticity magnitude, in Hz, at $t_p = 0$ ms. Bubble rising along the pipe center 64

22 Distribution of a) mean kinetic energy, in μJ; and b) vorticity magnitude, in Hz, at $t_p = 16.67$ ms. Bubble rising along the pipe center 65

23 Distribution of a) mean kinetic energy, in μJ; and b) vorticity magnitude, in Hz, at $t_p = 33.33$ ms. Bubble rising along the pipe center. 66

24 Distribution of a) mean kinetic energy, in μJ; and b) vorticity magnitude, in Hz, at $t_p = 50.0$ ms. Bubble rising along the pipe center. 67

25 Distribution of a) mean kinetic energy, in μJ; and b) vorticity magnitude, in Hz, at $t_p = 0$ ms. Bubble trajectory close to the pipe wall. 68

26 Distribution of a) mean kinetic energy, in μJ; and b) vorticity magnitude, in Hz, at $t_p = 16.67$ ms. Bubble trajectory close to the pipe wall 69

27 Distribution of a) mean kinetic energy, in μJ; and b) vorticity magnitude, in Hz, at $t_p = 33.33$ ms. Bubble trajectory close to the pipe wall. 70

28 Distribution of a) mean kinetic energy, in μJ; and b) vorticity magnitude, in Hz, at $t_p = 50.0$ ms. Bubble trajectory close to the pipe wall. 71

29 Distribution of turbulent kinetic energy, in μJ, at $t_p = 0$ ms. a) Bubble trajectory along the pipe center; and b) bubble trajectory close to the pipe wall 73

30 Distribution of turbulent kinetic energy, in μJ, at $t_p = 16.67$ ms. a) Bubble trajectory along the pipe center; and b) bubble trajectory close to the pipe wall 74

31 Distribution of turbulent kinetic energy, in μJ, at $t_p = 33.33$ ms. a) Bubble trajectory along the pipe center; and b) bubble trajectory close to the pipe wall 75

32 Distribution of turbulent kinetic energy, in μJ, at $t_p = 50.0$ ms. a) Bubble trajectory along the pipe center; and b) bubble trajectory close to the pipe wall 76

33 Turbulence intensity $\sqrt{\overline{u'u'}}$ in mm/s. The data presented are for $t_p = 33.33$ ms after the bubble enters the viewing volume. (a) Bubble trajectory along the pipe core; and (b) bubble close to the pipe wall 78

FIGURE Page

34 Turbulence intensity $\sqrt{\overline{v'v'}}$ in mm/s. The data presented are for t_p = 33.33 ms after the bubble enters the viewing volume. (a) Bubble trajectory along the pipe core; and (b) bubble close to the pipe wall..... 79

35 Turbulence intensity $\sqrt{\overline{w'w'}}$ in mm/s. The data presented are for t_p = 33.33 ms after the bubble enters the viewing volume. (a) Bubble trajectory along the pipe core; and (b) bubble close to the pipe wall..... 80

36 Reynolds stresses $\overline{u'v'}$ in mm^2/s^2. The data presented are for t_p = 33.33 ms after the bubble enters the viewing volume. (a) Bubble trajectory along the pipe core; and (b) bubble close to the pipe wall..... 81

37 Reynolds stresses $\overline{v'w'}$ in mm^2/s^2. The data presented are for t_p = 33.33 ms after the bubble enters the viewing volume. (a) Bubble trajectory along the pipe core; and (b) bubble close to the pipe wall..... 82

38 Reynolds stresses $\overline{u'w'}$ in mm^2/s^2. The data presented are for t_p = 33.33 ms after the bubble enters the viewing volume. (a) Bubble trajectory along the pipe core; and (b) bubble close to the pipe wall..... 83

39 Transient behavior of the kinetic energy in the test volume. Time 0 corresponds to when the bubble is first present in the viewing volume..... 84

40 Drag coefficient as function of Re_b. Full symbols present data where **u** = **0** and Ac = 0 in [55]. Open symbols present data where both **u** and Ac are included in [55]. See text for explanation..... 103

41 Drag coefficient comparison..... 105

42 Drag coefficient as function of the bubble rotation parameter..... 108

43 Lift coefficient as function of Reynolds number..... 109

44 Lift coefficient as function of rotation parameter..... 109

LIST OF TABLES

TABLE		Page
1	Camera calibration errors.	22
2	Bubble dimensions.	95
3	Speed and dimensionless parameters of the bubble.	98
4	Bubble acceleration magnitude and drag coefficient.	104
5	Bubble rotation parameter and oscillation frequency.	107
6	Bubble lift coefficient	111