Available online at www.sciencedirect.com
ScienceDirect
Chinese Journal of Aeronautics 22(2009) 349-354
Chinese Journal of Aeronautics
www.elsevier.com/locate/cja

Experimental Study of Motion of Nitrogen Taylor Bubbles and Liquid Slugs in Inclined Tubes

Zhang Hua, Wang Shuhua, Wang Jing*

Institute of Engineering Thermo-physics, Shanghai Jiao Tong University, Shanghai 200240,China

Received 22 July 2008; accepted 15 October 2008

Abstract

This article studies rising velocity of Taylor bubbles and liquid slugs in liquid nitrogen at different axial positions in upward inclined tubes by means of a high speed motion analyzer. The bottom-closed tubes in the experiments are 1.0 m long with an inner diameter of 0.014 m or 0.018 m. The tube inclines upward from 0° to 50° with respect to the normal. Statistical method is used to analyze the data of the Taylor bubble and the liquid slug velocity. Reflecting the effects of the inclination angle on the rising velocity of Taylor bubbles and liquid slugs, the experimental results indicate the similar trend the Taylor bubble velocity and the liquid slug velocity have: it increases first, and then decreases with the increase of the inclination angle. Moreover, with the increase of the inclination angle, the liquid slug velocity becomes greater than Taylor bubble velocity.

Keywords: cryogenic two-phase flow; rising velocity; high speed motion analyzer; liquid nitrogen; Taylor bubble; liquid slug; inclined tube

1. Introduction

Gas-liquid two-phase slug flow is inherently unsteady and highly complicated. It is characterized by long bullet-shaped bubbles separated by liquid slugs that may teem with small dispersed bubbles. Slug flow has found wide applications in variety of industries inclusive of transportation and handling of cryogenic fluids.

With rapid development of aerospace technology, cryogenic propellants are broadly used in rockets. In cryogenic engineering, the heat leak, the common phenomenon in conveyor and storage system of cryogenic liquid, unavoidably gives birth to cryogenic two-phase flow, which causes many troubles, such as pressure calculation, stable operation, stratification, geysers and eddies[1]. Phenomena pertinent to geysers could cause transient pressure surges and high vapor flow rates that sometimes might be large enough to damage equipment. They pose new problems to the application of multi-phase flow theory in the cryogenic engineering. Therefore, ever-increasing rising velocity of Taylor bubbles and liquid slugs in upward inclined conveying pipes becomes an important issue in cryogenic two-phase flow.

In many industrial applications, gas bubbles are trapped within an enclosed channel such as a cylindrical tube. If the ratio of the bubble diameter, d, to the tube inner diameter, D, be greater than 0.6, the tube diameter becomes the controlling length that dominates the velocity and frontal shape of gas bubbles[2]. Bubbles of this type are called Taylor bubbles and tend to be bullet-shaped. Between two consecutive Taylor bubbles, there is an abundance of liquid with small dispersed bubbles. This region is termed liquid slug. Taylor bubbles, therefore, occupy most of the cross-section of the tube. The surrounding liquid flows around the moving bubbles in the form of a thin film. A Taylor bubble is composed of two distinctive parts: a rounded nose and a cylindrical body surrounded by a thin liquid film. Should the length of the slug be more than $1.5D$, the bubble velocity is independent of the Taylor bubble length. A Taylor bubble without fixed length in a vertical or inclined tube is still regarded as a Taylor bubble. In this case, the Taylor bubble velocity depends upon the tube diameter, inclination angle, θ, and the physical properties (density, viscosity, and surface tension) of the liquid.

*Corresponding author. Tel.: +86-21-34206089.
E-mail address: wangj@sjtu.edu.cn
Foundation item: National Natural Science Foundation of China (50476015)

doi:10.1016/S1000-9361(08)60110-7

Bubble rise in stagnant fluid has long been an interested subject for extensive study and so far numerous publications can be found in the technical literature. In his early study, A. H. Gibson [3] discovered that bubble rise depends on the size of the bubble itself and the size relative to that of the tube. G. Barr[4] investigated the effects of bubble size, tube size, and viscosity on the bubble velocity. D. T. Dumitrescu [5] proposed the following Eq.(1) to calculate the drift velocity, U_d, of a single Taylor bubble in stagnant liquid, when the surface tension $\sum 4\sigma/(\Delta\rho g D^2) < 0.001$, where σ is the surface tension, $\Delta\rho$ the density difference between liquid and gas phases, g the gravitational constant.

$$U_d = 0.35\sqrt{gD} \tag{1}$$

R. M. Davies, et al. [6] provided a theoretical foundation to study bubbles in vertical tubes. Based on the assumed potential flow, they concluded that the Froude number (Fr) could be a constant in a vertical tube. Other important studies about bubble rise in vertical tubes were carried out by F. P. Betterton[7], H. L. Goldsmith, et al.[8], E. T. White, et al.[9], and R. A. S. Brown[10] and et al.

Bubble motion in inclined tubes has been studied by some researchers. E. T. White, et al.[9] noticed the influences of inclination angle on bubble rising velocity. E. E. Zukoski[11] studied the influences of inclination angle, viscosity and surface tension on the rising velocity. Bubble motion in inclined tubes inclusive of vertical and horizontal ones has also been studied by other researchers, such as C. C. Maneri, et al.[12], K. H. Bendiksen[13], M. E. Weber, et al.[14], B. Crouet, et al.[15], I. N. Alves, et al.[16] and R. van Hout, et al.[17-18]. All of them have revealed that the bubble velocity first increases and then decreases as the inclination angle increases.

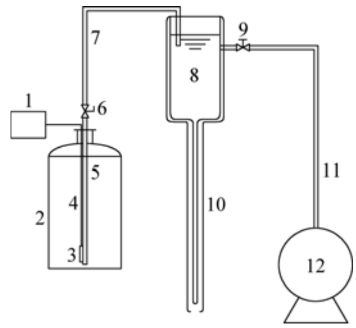
From the aforesaid review of the references concerning bubble rise in tubes, it is clear that most of the previous work has been devoted to the bubble motion in atmospheric temperature and in vertical tubes. For the Taylor bubble velocity and liquid slug velocity in cryogenic fluids in inclined tubes, could hardly be found any available reliable data.

The present study is meant to perform experimental investigation on the Taylor bubble velocity and liquid slug velocity in bottom-closed inclined tubes with liquid nitrogen as the work medium.

2. Description of Experiment

2.1. Experimental apparatus

Fig.1 shows the sketch of the experimental apparatus, which consists of a liquid nitrogen Dewar bottle, a test part and a vacuum pump as main components. The test part is made of double-layered Pyrex glass, which includes an upper tank and a cryogenic conveying tube (test section). The upper tank is 0.4 m long with an inner diameter of 0.1 m. The experimental tubes are 1.0 m long with inner diameters of 0.014 m and 0.018 m. The double-layered Pyrex glass can be rotated around its axis and fixed at one of inclination angles ranging from 0° to 50° with respect to the normal. Vacuumized by a vacuum pump to 6×10^{-2} Pa, the vacuum interlayer, 0.021 m clearance, functions as a thermal insulation to decrease the convection loss of heat.



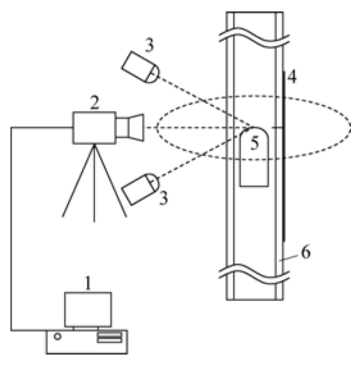
1—Power supply; 2—Liquid nitrogen Dewar bottle; 3—Electric heating rod; 4—Power cord; 5—Liquid nitrogen delivery tube; 6—Ball valve; 7—Flexible tube; 8—Upper tank; 9—Vacuum valve; 10—Test section; 11—Vacuum tube; 12—Vacuum pump

Fig.1 Experimental apparatus.

Stored in a Dewar bottle, the liquid nitrogen heated by an electric heating rod is supplied to the test section with the help of high-pressure nitrogen gas in the Dewar bottle. The liquid level of the upper tank is controlled between 1.16 m and 1.18 m to ensure the tube to be full of liquid nitrogen. Controlled by a power switch, the heating is stopped when the liquid level in the upper tank reaches about 1.18 m, and started when the level approaches 1.16 m.

2.2. Image processing system

Fig.2 shows the sketch of the image processing system, which is composed of a highspeed motion analyzer, a monitor, a light source and a computer. The highspeed motion analyzer (REDLAKE Motion-Pro®X3, 1 280×1 024 pixels resolution, 1 000 frame/s with the full resolution) is used together with a lens (AI NIKKOR 50/F1.2S) in the experiment, where the pixels resolution is 512×512, and the frame rate 1 000



1—Computer; 2—Highspeed motion analyzer; 3—Light; 4—Screen; 5—Taylor bubble; 6—Vacuum interlayer

Fig.2 A sketch of image processing system.