Experimental study on boiling flow of liquid nitrogen in inclined tube—liquid slug length distribution and velocity

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Abstract. An experimental study was carried out to understand the phenomena of the boiling flow of liquid nitrogen in an inclined tube with closed bottom by using a high speed motion analyzer. The experimental tube is 0.018 m ID and 1.0 m in length. The range of the inclination angle is 45-90º from the horizontal. The liquid slug length and velocity were studied. The mean liquid slug lengths increased first, and then decreased with decreasing θ, maximum at 60º, which showed the Taylor bubble was easier to coalescence from vertical to inclined, but coalescence lessening at 45º. The standard deviations of liquid slug lengths increase with increasing x/D at all inclination angles. The liquid slug propagation velocity increases first, and then decreases with decreasing θ, maximum at θ=60º, and is almost stable at 50D and 55D positions. These conclusions provide a basis for further study of the cryogenic two-phase slug flow.

1. INTRODUCTION

Gas–liquid slug flow is highly complex with an inherent unsteady behavior. It is characterized by long bullet-shaped bubbles separated by liquid slugs that may be aerated by small dispersed bubbles. Slug flow is found in many industrial applications one of which is transport and handling of cryogenic fluids.

With the development of current aerospace technology, cryogenic propellants are increasingly used in the missile industry. In cryogenic engineering, superheating always exists in conveyor and storage system of cryogenic liquid. So cryogenic two-phase flow is unavoidable. The propagation and storage of cryogenic liquids make many problems, such as stratification, geysering and rollover (Hands, 1988). Phenomena allied to geysering can cause high transient pressures and vapor flow rates, in some cases large enough to damage equipment. These bring new challenges on the application of the multi-phase flow theory in cryogenic engineering. Many researches were carried out to understand the liquid slug lengths which used normal atmospheric temperature liquid such as air-water and air-kerosene, and were carried out mainly for horizontal or slightly inclined slug flow and for vertical flow in developed slug flow (Nydal et al.1992; Brill et al.1981; Nicholson et al.1978; Andreussi et al. 1993; Cook et al. 2000; Griffith et al. 1961; Bernicot et al. 1989; van Hout et al. 1992; Costigan et al. 1997; van Hout et al. 2001; Mao et al.1989; Felizola et al. 1995; van Hout et al.2003). The liquid slug lengths distribution can be described by positively skewed distributions, such as the log-normal, the gamma, or the inverse Gaussian [Nydal et al.1992; Brill et al.1981; van Hout et al. 2001; van Hout et al.2003].
On the liquid slug lengths, the mean and maximum lengths were focused on study. For the horizontal tubes, the range of the mean liquid slug lengths varies from 10 to 100D (Nydal et al.1992; Brill et al.1981; Nicholson et al.1978; Andreussi et al. 1993). For the vertical tubes, the normalized mean liquid slug lengths vary between 10 and 20D with standard deviations between 30% and 50% (Griffith et al. 1961; Bernicot et al. 1989; van Hout et al. 1992; Costigan et al. 1997; van Hout et al. 2001). For the inclined tubes, the mean liquid slug length has a minimum of about 16D at 60º for air-kerosene slug flow (Felizola et al. 1995). R.van Hout, et al (2003) studied the evolution of the mean liquid slug lengths along the tubes at various inclination angles for air-water slug flow. The result shows the mean liquid slug lengths decrease with decreasing inclination angles.

Cryogenic vapor-liquid slug flow is seldom studied in inclined tube with closed bottom. Compared with normal atmospheric temperature liquid, cryogenic liquid has high compressibility, low density difference between vapor and liquid and low latent heat of vaporization. There are large differences on bubble motion in cryogenic two-phase flow and normal temperature two–phase flow.

The purpose of the present study is to investigate experimentally the distributions of the liquid slug length and the liquid slug velocity in inclined tube with closed bottom. The liquid nitrogen is used as working medium.

2. EXPERIMENTAL APPARATUS AND PROCESS

2.1 Experimental Set-up

Fig. 1 shows the schematic diagram of the experimental apparatus. The main body of the experiment, which is made of double layer Pyrex glass, includes a 0.4 m long stock tank with inner diameter 0.1 m, a 1.0 m long test sections with inner diameters, D, 0.018m. The main body of the experiment can be rotated around its axis and fixed at 40-90º inclination angles from the horizontal. The vacuum interlayer is 0.021 m, which is vacuumized by vacuum pump to serve as the thermal insulation to decrease the convection heat transfer. The degree of vacuum in vacuum interlayer is 6×10^{-2} Pa. The test part as a whole, only the upper end pipeline connected, so the heat leakage caused by the heat conduction is very small. The vacuum interlayer is vacuumized, so convection heat transfer is also very small. The main heat leakage on the pipeline is the radiation heat transfer.

The liquid nitrogen stored in a Dewar, which is heated by the electric heating rod, is supplied to the test section with the help of the high-pressure nitrogen gas in Dewar. The heating is controlled by a power Switch. The power switch is off when the liquid level of the upper tank is about 1.18 m, and is on when the liquid level of the upper tank is about 1.16 m.

2.2 High Speed Motion Analyzer

Fig. 2 is the schematic design of image processing system. The high speed motion analyzer (REDLAKE Motion-Pro® X3, 1280 ×1024 pixels resolution, 1000 frames/s with the full resolution) is employed in the experiment, together with a lens (AI NIKKOR 50/F1.2S). In the experiment, 512×512 pixels resolution is used with 1000 frames/s. The recorded images are transmitted to the computer for further analysis. Two photoflood lamps are used as light source, whose power is 1000W.

2.3 Experimental Condition

During the experiment, the range of inclination angles is 40–90º. The positions of 20D–55D from the bottom of tube are measured by using high speed motion analyzer.

2.4 Image Processing
The local propagation slug velocity of the bubble interface is calculated as the shift of the corresponding interface, divided by the time elapsed between the frames:

\[ U_{\text{Slug}} = \frac{x_2 - x_1}{n \Delta t} \]  

(1)

Where, \( x_1 \) is the bubble’s tail position of Frame \( n_1 \), \( x_2 \) is the bubble’s tail position of Frame \( n_2 \), see Fig. 3, \( n = n_2 - n_1 \), \( \Delta t = \frac{1}{f} \) ( \( f \) is the Frame rate).

The liquid slug length is determined by multiplying the residence time of the liquid slug over the measured position by the liquid slug velocity.

3. RESULTS

3.1 Liquid Slug Video Images Along The Tube at Various Inclination Angles

Fig.4 presents the evolution of the liquid slug along the tube at various inclination angles. The left of the video images (Fig.4) are the bottom of the leading nitrogen Taylor bubbles, and the right are the nose of the trailing nitrogen Taylor bubbles. Fig.4 indicates that small bubbles of liquid slug regions are more and more near the tube upper with decreasing angles.

3.2 Liquid Slug Velocity

The statistics data of liquid slug propagation velocity are listed in Tab. 1. Tab. 1 shows that liquid slug propagation velocity \( < U_{\text{LS}} > \) (m/s) increases first, and then decreases with decreasing \( \theta \), maximum at \( \theta=60^\circ \), and is almost stable at 50D and 55D positions. It should be noted that the standard deviation of \( U_{\text{LS}} \) (m/s) can approach about 0.10. This indicates small variability between individual slugs.

3.3 Liquid Slug Length Distributions

The histograms showing the distribution of liquid slug lengths are given in Fig.5. In general, the mean and the mode of the length distributions increase along the tube and the liquid slug length distributions are left-skewed in all cases.

The effect of the inclination angle on the measured liquid slug length distributions at different locations along the tube is shown in Fig. 5. The mean and the mode liquid slug lengths increased first, and then decreased with decreasing \( \theta \), maximum at \( \theta=60^\circ \), and the distributions become more inhomogeneous with decreasing \( \theta \).

3.4 Mean Liquid Slug Lengths and Standard Deviation

Fig. 6 present the evolution of the dimensionless mean liquid slug lengths as a function of inclination angle. In all cases, the values of \( L_{\text{mean}} \) are 3.5-5.5D at \( x/D=20 \) and increase to 7.5–9.5D at \( x/D=50 \), \( x \) the axial pipe distance measured from the bottom of the tube. The evolution of the slug length along the tube is hardly affected by the inclination angle, while the mean liquid slug lengths increased first, and then decreased with decreasing \( \theta \), maximum at \( \theta=60^\circ \), which shows Taylor bubble is easier to coalescence from vertical to inclined, but coalescence lessening at 45°. Similarly to \( L_{\text{mean}} \), the values of \( L_{\text{mean}} \) depend on the tube inclination as well, with the longest bubbles observed at 60°.

Fig. 7 presents the evolution of the dimensionless liquid slug lengths standard deviations as a function of inclination angle. Liquid slug lengths standard deviation increases with increasing \( x/D \) in all cases which shows liquid slug length distribution is inhomogeneous with increasing \( x/D \).
3.5 The Log-normal Distributions of The Liquid Slug Length

Fig.5 shows the liquid slug length distributions are left-skewed in all cases. The log-normal shape is fitted to the measured distributions and is depicted in Fig.5 as a solid line. The probability density function of the log-normal distribution is

\[
f(y) = \frac{1}{\sqrt{2\pi}\lambda\left(\frac{L_s}{D}\right)} \exp\left[-\frac{1}{2}\left(\ln\left(\frac{L_s}{D}\right) - \frac{\xi}{\lambda}\right)^2\right]
\]

where \( L_s \) is the values of the liquid slug lengths along the tube at various inclination angles, \( y > 0, \lambda > 0 \). The parameters \( \lambda \) and \( \xi \) in Eq. (2) are given in Tab. 2 for all cases.

4. SUMMARY AND CONCLUSIONS

An experimental study of the evolution of continuous liquid nitrogen boiling slug flow along inclined tube with internal diameters 0.018 m is presented. The hydrodynamic and statistical parameters include liquid slug length distributions and instantaneous velocity of liquid slug. The measurements were carried out by high speed motion analyzer at different positions along the tube. Through images analyzing, the small bubbles of liquid slug regions were more and more near the tube upper with decreasing angles.

Liquid slug propagation velocity increases first, and then decreases with decreasing \( \theta \), maximum at \( \theta=60^\circ \), and is almost stable at 50D and 55D positions. The standard deviation of \( U_{LS}(m/s) \) can approach about 0.10. This indicates small variability between individual slugs.

For all cases, measured length distributions were well described by the log–normal shape. The mean and the most mode liquid slug lengths increased first, and then decreased with decreasing \( \theta \), and the distributions became more inhomogeneous with decreasing \( \theta \), maximum at \( \theta=60^\circ \).

In all cases, the values of \( L_{mean} \) were 3.5–5.5D at \( x/D=20 \) and increased to 7.5–9.5D at \( x/D=50 \). The evolution of the slug length along the tube was hardly affected by the inclination angle, while the mean liquid slug lengths increased first, and then decreased with decreasing \( \theta \), maximum at \( \theta=60^\circ \), which showed Taylor bubble was easier to coalescence from vertical to inclined, but coalescence lessening at 45\(^\circ\). Liquid slug lengths standard deviation increased with increasing \( x/D \) in all cases which showed liquid slug length distribution was more inhomogeneous with increasing \( x/D \).

| \( x/D \) | parameters | 90\(^\circ\) | 80\(^\circ\) | 70\(^\circ\) | 60\(^\circ\) | 45\(^\circ\) | 40\(^\circ\) |
|---|---|---|---|---|---|---|---|
| 20 | \(<U_{LS}>\) | 0.30 | 0.33 | 0.34 | 0.44 | 0.35 | 0.33 |
|   | S.D. | 0.10 | 0.11 | 0.09 | 0.12 | 0.13 | 0.11 |
| 30 | \(<U_{LS}>\) | 0.33 | 0.36 | 0.40 | 0.46 | 0.36 | 0.35 |
|   | S.D. | 0.09 | 0.14 | 0.11 | 0.13 | 0.10 | 0.13 |
| 40 | \(<U_{LS}>\) | 0.34 | 0.36 | 0.39 | 0.43 | 0.39 | 0.39 |
|   | S.D. | 0.10 | 0.12 | 0.11 | 0.12 | 0.11 | 0.10 |
| 50 | \(<U_{LS}>\) | 0.38 | 0.37 | 0.38 | 0.39 | 0.34 | 0.30 |
|   | S.D. | 0.13 | 0.09 | 0.11 | 0.10 | 0.12 | 0.08 |
| 55 | \(<U_{LS}>\) | 0.39 | 0.38 | 0.38 | 0.39 | 0.35 | 0.31 |
|   | S.D. | 0.09 | 0.10 | 0.09 | 0.09 | 0.11 | 0.12 |
Tab. 2 Parameters a and b of log–normal fit

| angles | parameters | 20D | 30D | 40D | 50D |
|--------|------------|-----|-----|-----|-----|
| 90°    | λ          | 0.56| 0.62| 0.57| 0.67|
|        | ξ          | 1.34| 1.38| 1.66| 1.77|
| 80°    | λ          | 0.48| 0.8 | 0.29| 0.5 |
|        | ξ          | 1.42| 1.64| 1.58| 1.76|
| 70°    | λ          | 1.11| 0.5 | 0.35| 0.36|
|        | ξ          | 1.51| 1.55| 1.57| 2.06|
| 60°    | λ          | 0.43| 0.52| 0.4 | 0.23|
|        | ξ          | 1.77| 1.74| 1.9 | 1.76|
| 45°    | λ          | 1.07| 0.27| 0.43| 0.36|
|        | ξ          | 1.29| 1.51| 1.79| 1.76|

1. Power supply 2. Nitrogen dewar 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

1. Computer 2. High speed motion analyzer 3. Light 4. Screen 5. Taylor bubble 6. Liquid slug 7. Vacuum interlayer

Fig. 2 The schematic design of Image processing system
Fig. 3 Determination of the liquid slug length by image processing. Example for $\theta=45^\circ$, frame numbers 5 and 35. Frame rate =1000fps

Fig. 4 Liquid slug images along the tube at various inclination angles

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Fig. 5 Liquid slug length distribution along the tube at various inclination angles

Fig. 6 Liquid slug mean length along the tube at various inclination angles
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