Dynamic analysis of slug flow regime in two-phase flow

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1. Introduction

The bubble dynamics in the two-phase flow is complicated to be modeled but we have reliable model to estimate fortunately. However, they are working well for the one dimensional analysis only. Also, the three dimensional knowledge is requested in the industry strongly, but we have still confusion in the two-phase analysis. Especially recent arguments are set at the several points: (1) the flow regime transition between the slug flow and churn flow (2) flow regimes for the inclined tubes. We have been studied flow regime map for the inclined tube and we met both unsolved issues. In the center of the debate there was a slug bubble phenomenon. Therefore, we decided to study the dynamic and geometric characteristics of slug bubble in terms of the inclination and analytic understanding. As a first step of the study, we finished to design and construct the facility and instrumentation. And we are now studying the existing analytical models and comparing them with our experimental data.

2. Experimental Facility

An experimental facility to observe inclined two-phase flow was designed and fabricated. The system consists of four parts; (1) test section (2) arbitrary angle control system, (3) air-water supply system, (4) observation part. The overall system is supported by steel frame, and a test section is firmly attached to an angle control panel which can rotate around its axis from horizontal to vertical by a hoist on the top of the system. The hoist is constructed to ceiling and it changes the inclined angle by setting up and down the end of the angle control panel. The 2m long test section is made of transparent acrylic pipe with internal diameter of 0.025m. Impedance sensors are placed at 1/3 and 2/3 of the pipe and by using this, the chaotic two-phase flow can be analyzed. All the sections are connected with easily fastened and loosened flanges.

3. Analytical Model

3.1 Taylor bubble rise velocity

An ellipsoidal bubble rise velocity in a viscous liquid with an assumption of irrotational flow had been derived by T. Funada et al.(2005). It is expressed by a Froude number and determined by a Reynolds number, Eotvos number and the aspect ratio of the ellipsoid as follows. The eq.(1) is the formula of the rise velocity of an ovary ellipsoid derived.

$$-Fr^2e^2f_1^2(e)+\frac{1}{2}(1-e^2)-\frac{8Fr}{R_G}e\left[f_2(e)\left(\frac{1}{2}+\frac{e^2}{1-e^2}\right)+\frac{e^2f_1(e)}{1-e^2}+\frac{e^2f_1(e)}{1-e^2}\right]=\frac{8}{E_o}\frac{e^2}{1-e^2} \tag{1}$$

T.Funada et al. also expressed the formula of the rise velocity of a planetary ellipsoid as eq.(2).

$$-Fr^2e^2f_1^2(e)+\frac{1}{2}\sqrt{1-e^2}-\frac{8Fr}{R_G}e\left[f_2(e)\left(\frac{1}{2}-e^2\right)-e^2f_1(e)\right]=-\frac{8}{E_o}e^2\sqrt{1-e^2} \tag{2}$$

3.2 Taylor bubble length

The Taylor bubble length has been considered as a result of a force balance between the gravity force on the liquid film and wall shear stress. Ishii et al.(1984) suggested that because of the complete balance, there exists a small adverse pressure gradient and the liquids becomes unstable. The force balance on the liquid film around the slug bubble gives,

$$\frac{f}{2}\rho_f v_{fsb}^2\pi D=\frac{2}{3}\Delta\rho g A(1-\alpha_{sb}) \tag{3}$$

where the wall friction factor f is assumed to be in the form $f=C_f\left[\frac{(1-\alpha_{sb})v_{sb}D}{\nu_f}\right]^{-m}$ and with more assumptions of turbulence, the basic relationships for the two-phase mixture, the solution for the slug bubble length becomes

$$\sqrt{\frac{2\Delta\rho g L_b}{\rho_f}}=j+0.75\sqrt{\left(\frac{\Delta\rho g D}{\rho_f}\right)\left(\frac{\Delta\rho g D^3}{\rho_f \nu_f^2}\right)^{\frac{1}{18}}} \tag{4}$$

According to this equation, the slug bubble length depends on superficial velocity, tube diameter and flow properties. This theory had been reported that it shows general trends, but it does not give well-matched prediction.

4. Experimental Results and Discussions

4.1 Visualization method

The phenomena of two-phase are observed by two methods; using high speed camera and impedance signal. The high speed camera is capable of 32,000 fps recording, capturing of 512 by 512 pixel resolutions, accepting external triggering signals. With halogen lighting system, the flow is observed. Simultaneously, averaged void-impedance signal is also measured and recorded by digital acquisition system at sampling rate of 100Hz, for 60 seconds. To analyze Taylor bubble delicately, void impedance signal was studied precisely. By synchronizing two signals, two-phase flow is observed by high speed camera and impedance signal at the same time. As comparing them one to one each other, void impedance signal can be understood its behavior more precisely. Once the reliable and accurate method of extracting slug information from the void impedance signals is developed, then the method can generate a number of data from existing two-phase flow signals. Fig.1 shows rising bubble for 3seconds and its signal. By concentrative observation of bubble nose and tail parts, it was found that the signal changes drastically when the bubble nose get in the area of impedance electrode exists. Even though the quantitative value is not constant, a derivative would be greatly changed.

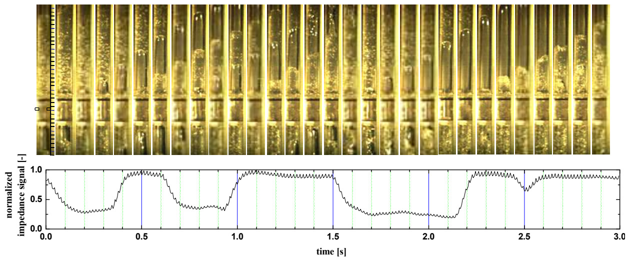

Fig.1 rising bubble and its impedance signal (3s)

A bubble nose distinction is possible by using derivatives. On the other hand, at the bubble tail, the signal does not be changed as at bubble nose because of irregular interfacial cross-section and trailing bubbles. Therefore, an assumption is adopted, as follows. (1) slug bubble shape is very transient, (2) even though it changes its shape very frequently, slug bubble shape is one of among those three type of shape in Fig.2., (3) we can assume the slug bubble length of (c) is same to that of (a) if bubble (a) changes to (c) according to times.

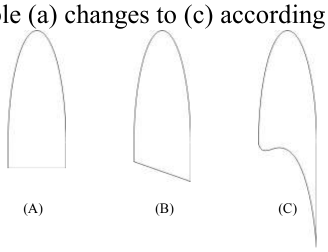

Fig.2 Three possible slug bubble shapes

Then, it is possible to estimate the slug bubble length of (c) at the moment the bubble (c) changes its shape to (a). eq.(5)

$$\overline{\Delta t_{TB}} = \frac{A\cdot\int 1-\alpha(t)dt}{A\cdot\left(1-\alpha(t)\right)_{max}}, \quad where\ A=\frac{\pi d^2}{4} \qquad (5)$$

Even if flow velocities become higher so the arbitrary character of bubble (c) becomes extreme, this method to determine slug bubble length is still remained as the most firm and reasonable one.

4.2 Results

With electrodes equipped at test section, void impedance signal is measured at various conditions. Fig.3 shows example of void signals of vertical upward flow. From left-top side to right-bottom side jg is

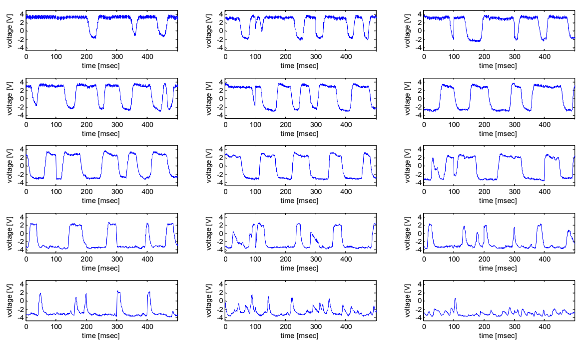

Fig.3 Two-phase flow void impedance signals

increasing by 0.02, 0.03, 0.05, 0.07, 0.1, 0.13, 0.16, 0.23, 0.3, 0.46, 0.62, 0.82, 0.99, 1.64, 2.3 m/s, when jf is remained at 0.025 m/s constantly. It is clearly shown that as jg is increasing the bubble signals get larger and distorted, and it is head to churn signals fluctuating at low level.

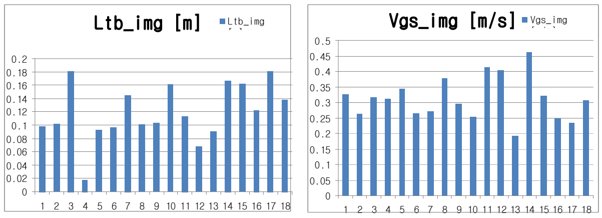

Fig.4 the results of visualization analysis; (a) slug bubble length, (b) slug bubble rising velocity

By observing Taylor bubble and that of impedance signal simultaneously, it was found that the impedance signal changes very sensitively at bubble noses, but not at bubble tails. Critical method has been made to determine exact slug tails which can derive slug bubble length. It is applied to a slug flow with low flow rate, and found that the rising velocity was well matched but the bubble length was shown a difference with the theory (Drift flux model). Further detail analysis is required and planned.

5. Conclusions

The vertical slug flow regime has been studied using visualization method to evaluate existing analytical models which has been used for the flow regime transition criteria in the inclined tube facility. High speed camera synchronized with the impedance meter to measure the void fraction provided accurate measure of the bubble length and rising velocity. The present results show that there is small error in the model of the drift velocity but the length should be improved due the large deviation between the present experimental data and previous model.

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