On two-phase flow models for Coriolis flowmeters

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Abstract

This paper reviews main previous works on the models of Coriolis flowmeter behaviour in two-phase flow. By experiment of bubble flow in vertical pipe with/without external vibration, some useful phenomena were observed. A general solution was obtained to the dynamic equation of a bubble motion. Some comments were given to the prediction of measurement errors by Coriolis flowmeters. Main points are: In most cases bubble shape is not sphere, but flat. Flat bubbles will be easy to move along a non-straight orbit, this causes transverse motion of the bubble. The transverse motion of bubbles are in a random way. Finally, this self-induced transverse vibration will affect the measurement of density and flowrate by a Coriolis flowmeter. It may be an intrinsic error source which is hard to eliminate. The paper also gives standard deviation and uncertainty of the random vibration in the experiment with various gas flowrate.

1. Introduction

A Coriolis flowmeter measures flowrate by force. It is considered as 'real' mass flowmeter [1]. Late in last century, people started to pay attention to behaviour of Coriolis flowmeters under multiphase flows [2]. In 2003, Hemp and Hoi gave a 'bubble model' [3]. Later Hemp and Kutin (2006) commented that 'compressibility change' would happen when liquid was mixed with gas [4]. Others also tried to model the behaviour of Coriolis flowmeters under multiphase. Weistain in his Ph D thesis [5] focused on 'decoupling' problem, which was defined as slipping of gas from liquid in the mixture. He concluded that smaller bubbles and external vibration would help to reduce measurement error; Gysling (2007) gave an aero-elastic model [6], and declared that acoustic speed of mixture could be used to correct the result by the flowmeter; Basse (2016) studied damping of the flowmeters due to 'decoupling'. He concluded that for small bubble and small void fraction, the damping was proportional to the void-fraction [8]. Liu et al (2001), instead used neutral network technology to obtain better readings for the flowmeter [7].

The 'bubble model' assumes small size of bubble, no interaction between bubbles, small vibration amplitude, as well as no change in diameter ('solid bubble'). Based on these assumptions and by classic fluid mechanics [9], it is deduced that a quantity of liquid equivalent to a half of the bubble volume will move with the bubble. This part of liquid is called as 'added mass' (or induced mass) of the bubble.

Further deduction using the 'added mass', it is concluded that, if a liquid with bubbles is doing vibration, the bubble's speed or acceleration is three times as that of the liquid. The 'bubble model' leads to measurement errors of a Coriolis flowmeter for water-gas two-phase flow as:

$$\mathrm{E}_{\rho} = -3\alpha \qquad \mathrm{E}_{\dot{m}} = -\frac{2\alpha}{1-\alpha}$$

where E_{ρ} is the percentage error of two-phase density, $\mathrm{E}_{\dot{m}}$ is the percentage error of two-phase flowrate, α is the void fraction：

$$\alpha = \frac{\text{gas volume}}{\text{water volume+gas volume}}.$$

There are researchers doing experiments to look at the ability of Coriolis flowmeters to measure multiphase flows. A summary of some measurement errors by Coriolis flowmeters is given in Table 1:

Table 1 Errors of Coriolis flowmeter in multiphase flow (Test data)

Author	**Coriolis meter installation**	**Fluids**	**Void fraction**	**Max. Error**
Skea and Hall	Straight, Curved	Oil+N2	6% N_2 9% N_2	-15% +5%
		Water	Max.	0.3%(small)

	3 others	in oil, Oil in water	15%	Not work
Wang et al	Vertical Horizontal	Liquid and gas CO_2	0~70%	-16%~2% -4%~14%
Michael et al	normal	High viscous oil N_2	0~90%	±2% ±5%
Liu et al	U type	air, water	0~35%	0~-25%
B B Tao et al	U type, horizontal	Gas, water	0~25%	2%~-22%
Weinstein	U type, up/down	Gas, water	0~8%	Up: -15%, down: 12%

It shows that Coriolis flowmeters experience accuracy problem in multiphase flows. The questions are: Is it because we have not good models for the flowmeters? Or because certain intrinsic property of the flowmeters? Further investigation is thus still needed.

2. Experiment observation

We have undertaken some experiments. The goal was to observe the bubble behaviours for studying model for Coriolis flowmeter under two-phase flow.

Experimental system includes a Perspex tube vertically set, with a bearing on bottom and an elastic support on top, an electromagnetic exciter to make the tube vibration around an axis through the bearing. Air is pressed into the water in the tube from the bottom, with a control of the air flowrate. Bubbles moving upward the top of the tube are pictured using high speed camera. Vibration of the pipe is measured by eddy-current displacement sensor.

Since photos taken by high speed camera are in large numbers, only two typical photos are shown in Figure 1. The left is bubbles rising in a state pipe, while the right is bubbles rising with external excitation.

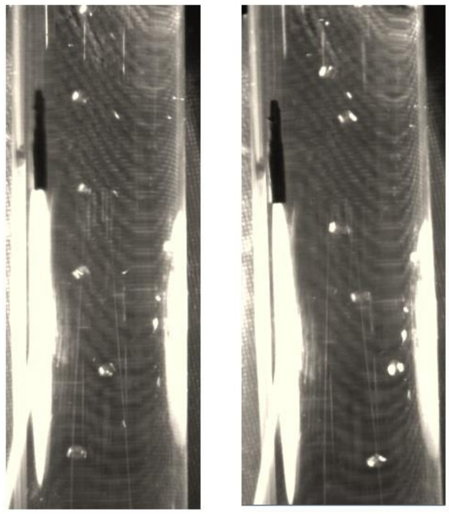

Figure 1: Rising bubbles without (left) and with (right) external excitation

By comparing many pictures taken by camera, difference of bubble behaviours with and without tube vibration is observed. Main phenomena are as follows:

1. The shape of the bubbles observed is not in sphere, rather is a flat one or even disk like. Diameter of the bubbles are 1~3 mm, which is within most industry cases. This would leads to increase of the 'added mass'.

2. These flat bubbles change their orientation while moving upward in non-straight orbits. This is self-induced under no external vibration. In the observation, the flat faces seem always point to the motion direction.

3. Difference of bubble speeds between tube vibrating and non-vibrating states is not obvious in the experiment. Exciting frequency is between 2~40Hz, with maximum amplitude from 1 mm to 0.1mm depending on the frequency.

4. A bubble flowing in water itself will induce random vibration. The vibration has a certain relation with void fraction of the air. It is linear for small void fraction.

An explanation for above phenomena is as bellow: When a bubble moves relatively to fluid, it carries a part of front fluid with it ('added mass'). The resistance of this part of fluid makes the bubble become flat. A flat bubble experiences different resistances in different directions. So the bubble tends to move in side direction where resistance is smaller rather than in front direction. Here is transverse motion. But transverse motion in turn carries the fluid in side direction with bubble. Due to the resistance, the bubble changes its shape to have the flat face pointing to the new direction. This change of motion direction depends on balance of forces on the bubble. Occurrence time is random.

3. On theoretical model

To predict the behavior of a Coriolis flowmeter in two-phase flow, we need a model to predict bubbles' behavior. For this, model similar to previous references is used but with some changes of terms. We firstly consider a gas bubble (of size in industry cases) in a vertical water pipe up flow under transverse vibration. Mass of the air is neglected compared with water. Rather, added mass is considered [9][10]. Transverse motion for a bubble in this case can be equated as:

$$m_{in}\frac{d^2x}{dt^2}+c\frac{d(x-y)}{dt}=m_w y_0\omega^2 e^{i\omega t} \qquad (1)$$

where m_{in} is called 'added mass' of the bubble, m_w is the mass of water in same volume of the bubble, c is the damping caused by relative motion (slipping) of m_{in} in water, x is the absolute displacement of the bubble, y is the displacement of the fluid. It is supposed being the same as that of the pipe. The pipe is doing harmonic transverse motion with an angular frequency of ω, with amplitude of y_0.

The solution of Equation (1) is:

$$x(t) \quad = x(0)+v(0)\frac{m_{in}}{c}\left(1-e^{-\frac{c}{m_{in}}t}\right)+x_0 e^{i\omega t+i\varphi} \qquad (2)$$

where x(0) and v(0) are transverse displacement and transverse velocity at t=0 respectively. The time t=0 should be the moment when transverse velocity caused by the bubble itself becomes non-zero. In observed phenomenon 2, bubbles will do transverse motion randomly, x(0) and v(0) seem being random too.

The steady state solution of x(t) has a form of

$$x(t)=x_0 e^{i\omega t+i\varphi} \qquad (3)$$

$$\text{with} \quad \mathrm{tg}\varphi=\frac{(m_{in}+m_w)c\omega}{m_{in}m_w\omega^2-c^2} \qquad (4)$$

$$x_0=y_0\frac{\sqrt{(m_{in}+m_w)^2(c\omega)^2+(m_{in}m_w\omega^2-c^2)^2}}{m_{in}^2\omega^2+c^2} \qquad (5)$$

where x_0 and y_0 are the magnitudes of bubble and pipe displacements respectively. In the extreme case of c=0, φ will be 0, and $x_0=y_0\frac{m_w}{m_{in}}$. For solid spherical gas bubble where 'added mass' is 1/2 mass of bubble volume with water, $x_0=2y_0$. In the experiment, we only observed oblate gas bubble. If we take the 'added mass' as 0.7~0.95 times of water of the bubble volume as for oblate bubble [10], then $x_0=(1.4\sim1.05)y_0$. It seemed closer to what we got from experiment. If the 'added mass' is the same as the fluid mass in the bubble volume, $m_{in}=m_w$, then $x_0=y_0$. This is the case of no bubble.

Equations (2) to (5) are usually used to estimate errors in density and flowrate measurement. However, in observed phenomenon 4, there is another force of f(t,α), which caused by bubble random motion. It is a random force as well. If we look at Equation (2), we find the second term is non-zero as long as there is transverse random motion of a bubble. The random property of v(0) makes it hard to predict x(t). However, we are able to measure the vibrations of a pipe with bubble flow but without external excitation. A typical vibration is seen in Figure 2, where as a comparison, vibration of the pipe with water only under external excitation is also plotted.

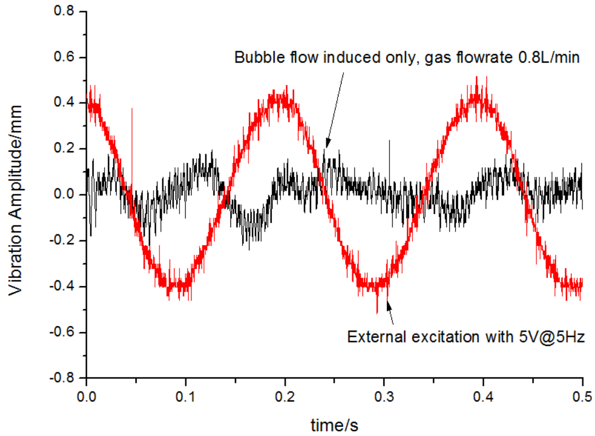

Figure 2: Bubble induced vibration compared with external excited vibration

Standard deviation of the bubble induced random vibration are given in Table 2 for various gas flowrates.

Table 2: *Standard deviation of bubble flow induced vibration*

Gas flowrate(L/min)	0.4	0.8	1.2	1.6
Standard deviation with uncertainty	0.053 ±0.003	0.083 ±0.002	0.148 ±0.035	0.235 ±0.067

From Table 2 we can see that, as gas flowrate becomes larger, the uncertainty of standards deviation becomes larger as well. The relation of the standard deviation with the void fraction of gas has a similarity to pipe damping in bubble flow [11].

So if we are to estimate the measurement errors of a Coriolis flowmeter, the error caused by bubble's random transverse motion needs to be considered. Since the random force seemed not be able to predicted, it may cause intrinsic measurement error in Coriolis flowmeters unless we can eliminate it.

4. Summary

We undertook experiment of bubble flow in water in a vertical pipe. Some interesting phenomena were observed. These help us to study further the existing models for a Coriolis flowmeter under water-air two-phase flow. We found there are a few things need to re-consider:

1. Solid sphere bubble model needs to be changed. By this, the 'added mass' will be more than half of the bubble volume.

2. After assigning the 'added mass' for the bubbles, damping would be the viscous friction of the liquid to the 'added mass'. Here boundary layer theory world work.

3. By solving the dynamic equation of a bubble in transverse vibration fluid. Expression of the bubble motion was obtained. It includes terms for transient state for bubbles, which relates to self-induced random transverse motion of bubbles

4. There is a random force caused by random motion of bubbles. The effect may be measured but hard to predict by models. Random force may cause an intrinsic error on Coriolis flowmeter in two-phase flow.

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