Investigation of Turbine Flowmeter Response in Vertical Air-water Two-phase Flow

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Abstract

Response of turbine flow meter in a vertical air-water two-phase flow is experimentally investigated. The flow field and the transient response of turbine are captured through a high speed camera, and the cross-sectional phase distribution is recorded by arrayed ERT. The experiment reveals that the rotational rate of the turbine drops when air intrudes into the rotor, and the relative fluctuation amplitude of the rotation decreases with the water flow. For the benefit of combined flow measurement with ERT and turbine meter, an extension to TG turbine performance model involving the non-steady two-phase effects is implemented. It is found that, given the ERT phase information, the extended model may well depict the response of turbine flowmeter in two-phase vertical flow.

Key words: Turbine flowmeter, air-water flow, turbine performance model，ERT

1. Introduction

Turbine flowmeter has been widely used to measure normally the single-phase flow rate. Besides, extended uses of it in two-phase flow are also common, e.g. in field exploration of oil or gas where gas-liquid vertical flow is frequently seen. The response of turbine flowmeter in such abnormal conditions may be influenced by many factors such as the slip between phases, the flow pattern, and so on, which is of great complexity and has received considerable attention over the years [1]. In practice, serving generally as a part of the multiphase flow meter (MFM) in charge of global mass or volume rate [2], turbine flowmeter is determinative to the measuring accuracy of MFM.

Researches on performance of turbine flowmeter in multiphase flow are abundant. Relevant advances have been comprehensively reviewed by Baker [3]. Theoretical modelling of meter performance presents one of key issues with respect to turbine flowmeter. A simple and popular approach to involve the multiphase effect is to consider a steady and homogeneous flow on basis of large-scale average over time and space [4,5]. Kamath and Lahey [6] proposed a non-steady model instead, and analysed factors that may affect the meter performance in transient two-phase flow. By comparison, inadequacy of quasi-steady models was identified therein. Above all, those models basically assume a uniform distribution of phases which is a reasonable approach for well-mixed flow patterns such as the fine bubbly flow while goes invalid for those with large interfaces such as the slug flow and the stratified flow.

Experimentally, to compose the full profile of a multiphase flow, pure output of turbine flowmeter is insufficient, and a joint measurement with other instruments is normally required. Global density and void fraction are two common supplementary quantities that are easily accessible in reality [7-10]. The extra information of void fraction may help to discriminate the local flow pattern and hence to establish a more sophisticated link between flowrates and turbine response. Nevertheless, to realize a universally reliable mapping among turbine response and varied phase distribution and velocity profile remains an enormous challenge. Accurate prediction as well as quantitative explanation of the turbine response under multiphase condition is still far beyond reach.

In this paper, an experimental investigation on the response of turbine flowmeter in a vertical air-water two-phase flow is carried out. Combined diagnosis with high-speed videography and electrical resistance tomography (ERT) is performed. We also made an extension to the original Thompson-Grey (TG) turbine performance model [11] to examine the non-steady two-phase effects.

2. Experimental setup

A gas-liquid vertical pipe system is established for the current test. Air and water flows are separately pumped and monitored, and mixed through a T-junction before they enter the test section. The flow is upward. As shown in Fig. 1, the testing turbine flowmeter is connected in middle of the test section. For convenience of flow observation in some tests, the turbine rotor is replaced by a bare hub. A self-developed ERT system with 8x8 arrayed conductive probes [12] is mounted above (downstream) the flowmeter to record the cross-sectional phase distribution, by which water content may be easily derived. The flow in pipe as well as the movement of the turbine rotor, is directly filmed through a high-speed video camera. Digital image processing is further employed to extract the transient rotor speed from the video.
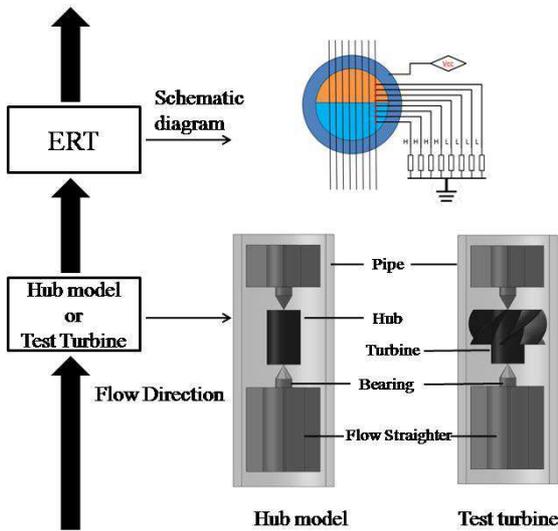

Fig.1 Schematic of experimental setup

3. Theoretical model

TG turbine performance model has been proven competent for description of turbine behaviour in steady single phase flow, but not for that in non-steady multiphase flow. Therefore, extensions have to be made for current application. According to Newton's law, the rotation of turbine follows

$$T_d - \sum T_r = J \frac{d\omega}{dt} \qquad (1)$$

where, T_d is the driving torque, T_r the retarding torque, J the moment of inertia of the turbine rotor and ω the transient rotor speed. Thereby, the equation restores its original non-steady form.

The driving torque is the most important one. By assuming an axisymmetric flow profile, it can be integrated along radius

$$T_d = N \int_{R_h}^{R_t} \frac{1}{2}\rho(r)U(r)^2 c(C_L \cos\beta - C_d \sin\beta) r dr \qquad (2)$$

with R_h the hub radius, R_t the blade tip radius, N the blade number, $\rho(r)$ and $U(r)$ the flow density and velocity at radius r, c the chord of blade, C_L and C_D the lift and drag coefficient of a flat blade, and β the twisted angle between the flow direction and the meter axis.

For single phase flow, density ρ is constant and the inlet velocity U applies a known steady profile. In multiphase flow, however, the velocity and density distributions are transient and far more complicated. We try to model the time-dependant phase and velocity profiles based on the measuring of arrayed ERT.
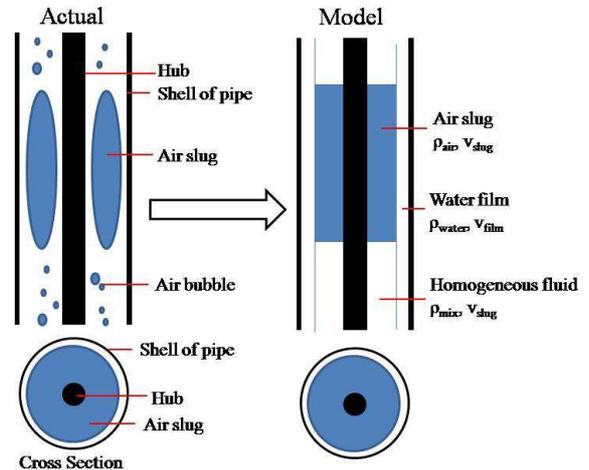

Fig.2 Modelling of slug flow

As sketched in Fig.2, for slug flow, the actual phase distribution is simplified as an axisymmetric assembly of three regular parts. The flow rates of respective phases then satisfy

$$\begin{cases} v_{slug} S_{slug} [f_{slug} t_{slug} + a_{air}(1 - f_{slug} t_{slug})] = \dot{V}_{air} \\ v_{slug} S_{slug} a_{water}(1 - f_{slug} t_{slug}) + v_{film} S_{film} = \dot{V}_{water} \end{cases}$$

(3)

where, S_{slug} is the cross-sectional area of the air slug, S_{film} is the area of the water film, a_{air} is the average air content of the homogeneous water column ($a_{water} + a_{air} = 1$), f_{slug} is the average sweeping frequency of air slug, and t_{slug} the average duration of it. The above quantities may all be measured by ERT. The two unknowns are v_{slug} – the velocity of the air slug, and v_{film} – the velocity of the

water film. These two can be solved by equation (3), which finally completes the reconstruction of the whole flow field.

The two-phase effect of the homogeneous water column is fulfilled by a modification of the overall density. That is, to replace the density in equation (2) with an averaged one

$$\rho_{homo} = a_{air}\rho_{air} + a_{water}\rho_{water} \tag{4}$$

Similar treatment is employed for well-mixed flow patterns without large-scale interfaces.

4. Results and discussions

The present study examines an air flow varying from 0.06 to 0.50m³/hour and a water flow from 0.2 to 1.6m³/hour. Following the classification of Julia et al. [13], three typical flow patterns -- Slug(S), Cap-Slug (CS) and Bubbly (B) -- are observed in the hub annulus.
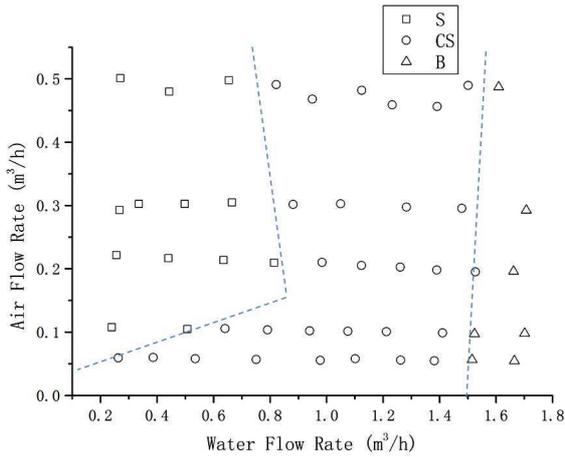

Fig.3 A map of flow patterns in hub annulus of a turbine flowmeter

Fig. 3 shows the distribution of the three flow patterns along phasic flow rates. It is clear that the slug flow collects in the region of low water flow and high air flow while the bubbly flow occurs mainly at high water flow (larger than 1.5m³/hour). The cap-slug flow, as a transitional regime between the above two, collects in the middle region where water flow is moderate.

Average air slug frequency and duration are captured by ERT and demonstrated in Fig.4. As expected, the duty cycle of the air slug, i.e. $f_{slug}*t_{slug}$, decreases with the inlet air cut. For higher air flow, the decrease of duty cycle is mainly casued by the shorten of air bubble duration; and for lower air flow, it is largely due to the

drop of bubble frequency. When the water flow exceeds 1.5m³/hour, slugs or big bubbles become rare which are merely detected in the test.
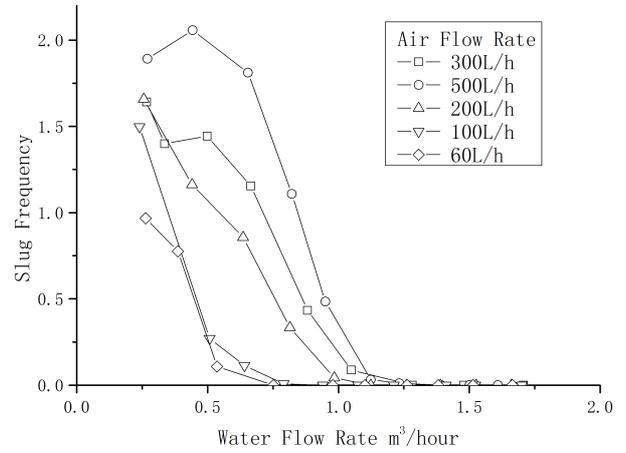
(a)
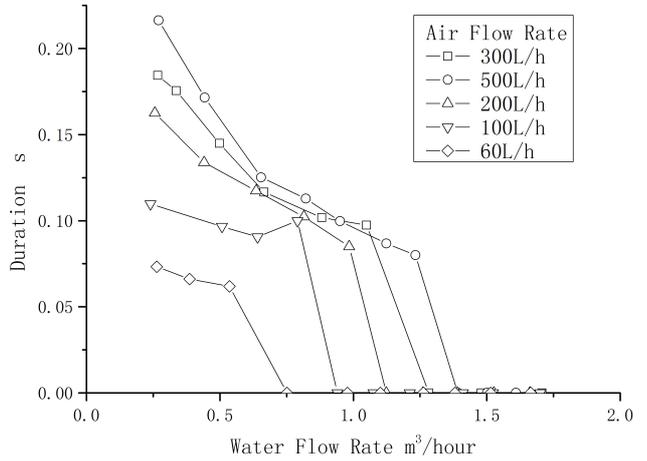
(b)

Fig.4 Slug information: a. Frequency, b. duration

The corresponding average output frequency of the meter is shown in Fig.5. Similar to that in pure water, the frequency of the rotor increases almost linearly with the water flow for a fixed air flow. The meter factor K depends on the air flow, though. Specifically, the addition of air flow tends to level down the volume based K factor and level up the mass based K factor.

Fluctuations of the meter output are observed. The rotational speed of the turbine drops quickly when an air slug or big bubble intrudes into the rotor, due to the relatively weaker driving capability of gas than liquid. When the water flow is small, a fast ascending of air slug may even cause a temporarily reversed flush of the outer water film due, which in fact imposes a negative driving torque on the rotor.
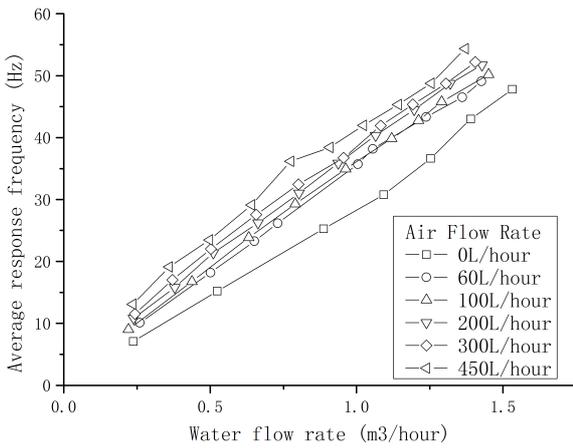
Fig.5 Average response frequency of the turbine flowmeter in air-water two-phase flow
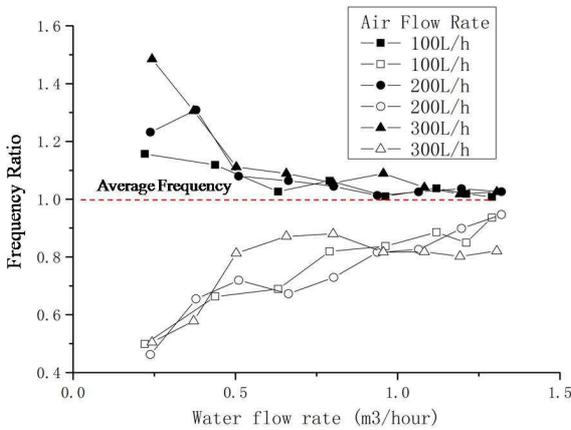

Fig.6 Fluctuations of turbine flowmeter response in air-water two-phase flow

As an indicator of the rotational stability, the maximum and minimum of the transient rotor frequency with respect to the average for three air flow conditions are shown in Fig.6 for comparison. The relative fluctuation amplitude of the response frequency is found to decrease with the water flow. That means the faster the liquid phase is the more stable the response of turbine flowmeter will be. By contrast, the air flow does not present a significant and clear influence on the fluctuation amplitude, despite that when the water flow is extremely low a larger air flow seems to cause a higher maximum frequency.

Theoretical calculations with the model presented in previous section are performed to re-examine the current test cases and to verify the model as well. The model is first applied for a calculation of turbine response in pure water. Decent agreement with the experimental results is reached. On this base, we proceed to calculate the two-

phase cases with the supplement of ERT data such as the slug frequency and duration. Fig. 7 shows the calculation results. Comparing with Fig.6, one may find that, the features of rotational fluctuation in reality, including the variation tendency, are well depicted by the model.

It will be beneficial if by combined use of the arrayed ERT and the turbine flowmeter one may precisely determine the air-water two-phase flow. The theoretical model may serve as a useful tool for the explanation of the raw data from both instruments, and the preliminary results are encouraging.
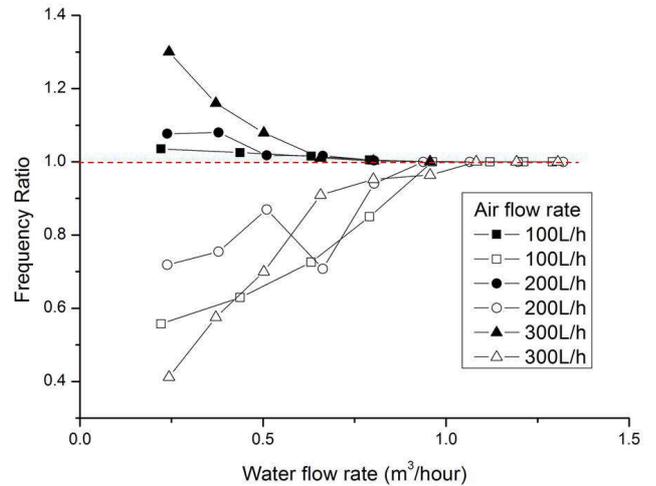

Fig.7 Fluctuations of turbine flowmeter response predicted by theory model

5. Conclusion

The performance of a turbine flowmeter in an air-water two-phase vertical flow is experimentally investigated. We also attempt a theoretical modelling of the turbine response in such conditions. The main conclusions are as follows:

◆ The average response frequency of turbine flowmeter is roughly linear to the flow rate when the air flow is fixed. And the relative amplitude of the fluctuations in frequency decreases with the water flow.

◆ The distribution of gas phase has a significant influence on the turbine response. In upward vertical flow, the rotational speed of turbine drops quickly when air slug or big bubble passes.

◆ A theoretical model involving the non-steady two-phase effects is developed and preliminarily verified. It shows the potential of realizing a precise

measurement of multiphase flow by combined use of arrayed ERT and a turbine flowmeter.

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