Experimental Measurement and CFD Simulation for Characterization of Coriolis Flowmeter Performance

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Abstract. Gas-liquid two-phase flow measurement is challenging in comparison to single phase flow measurement as their dynamics are more complex. This study aims to investigate the performance of a U shape Coriolis mass flowmeter (CMF) to measure gas liquid two-phase flow via both experimental measurements and numerical simulation. It was observed from both measured and simulation results that the measurement performance of CMF was mainly affected by variation of mixture density and variation of flow pattern associated with gas entrainment. The findings provide fundamental fluidic dynamics of on-line multiphase flow measurements in harsh environments.

Key words: Coriolis Mass flowmeters, Gas-liquid two-phase flow, Gas Volume Fraction, Fluid Structure Interactions.

1. Introduction

Coriolis mass flowmeters (CMFs) are used to measure the bunker fuel and LNG in recent years. However, during the bunkering process and boil-off gas (BOG) of LNG, the entrained gases in liquid flow may occur, where the two-phase flow can cause the significant errors of the measurement by CMFs [1, 2]. A number of studies have been carried out to investigate CMFs’ performance on gas-liquid two phase flow, including the bubble theory [3] & the Lumped Parameter Aeroelastic model [4]. These studies focus on mathematical model development or optimization, but were not validated by experiments. Thus, it is crucial important to predict the performance of CMF on gas-liquid two-phase flow by a validated computational fluid dynamics (CFD) model.

In this study, the measurement performance of a U-shape Coriolis mass flowmeter (CMF) on measuring gas liquid two-phase flow were conducted on both experimental measurements and numerical simulations. The effects on some important parameters including variation of mixture density, change in pressure and gas void fraction (GVF) on the CMF were investigated via both lab experiments and a fluid structure interaction (FSI) CFD model.

2. Methodology

2.1 Experimental Measurements

The experiments were carried out on a liquid flow calibration system with a U-shape Coriolis flow meter in National Metrology Centre (NMC), Singapore. Water flows through a U-shape CMF, CMF200, from 50 kg/min to 600 kg/min, and the batch water is measured by a reference balance Mettle
Toledo KCS600 based on gravimetric method. To generate gas-liquid two-phase flow, nitrogen gas with flow rate was injected from 3 l/min to 10 l/min at 6 bar at the upstream of CMF200.

2.2 Numerical modeling and simulations

A CFD model of a single tube of a CMF was designed as shown in Fig. 1. The model is developed for simulations and the results are extended to two parallel tubes. The meter’s pipes are made of 316L stainless steel with density, 8070 g/cm³ and Young modulus of elasticity 1.93x10¹¹ Pa. The CMF model was built in AutoCAD software, Autodesk Inventor Professional 2016, and imported to ANSYS for simulations. The tube’s volume & mass are 2.5368x10⁻⁵ m³ and 0.20472 kg, respectively. A magnetic coil oscillates the flow tube at point C at the natural frequency of the tube. Two sensors, S1 and S2, pick up the displacement of the inlet and outlet section of tube at two symmetrical points, A and B.

![Fig. 1 CFD model of a U-shape tube](image)

The governing equations for the fluid domain are the mass conservation equation Eq.1 and momentum equation Eq.2, in integral form, in three-dimensional spatial distribution. The governing equations were modified to include the effects of surrounding boundary motion.

\[
\frac{d}{dt}\left(\int \rho_M d\Omega\right) + \int \rho_M (v_F - v_S) \cdot n d\Gamma = 0
\]  

\[
\frac{d}{dt}\left(\int \rho_M v_F d\Omega\right) + \int \rho_M v_F (v_F - v_S) \cdot n d\Gamma = \int f_F d\Omega + \int \sigma_F \cdot n d\Gamma
\]  

where: \(\rho_M, f_F, \sigma_F, v_F\) and \(v_S\) are mixture density, unity volume force acting inside the volume \(\Omega\), unity surface tension force, fluid velocity and surrounding boundary velocity respectively.

The mixture average density is

\[
\bar{\rho}_M = GVF \times \rho_N + (1 - GVF) \times \rho_W
\]  

where \(GVF, \rho_N\) and \(\rho_W\) are gas volume fraction, nitrogen gas density and water density, respectively.

Water was used as primary phase with volume flow rate \(Q_W\) and nitrogen gas was considered as an auxiliary phase with volume flow rate \(Q_{N2}\). The gas volume fraction is determined by

\[
GVF = \frac{Q_{N2}}{Q_{N2} + Q_W} \times 100\%
\]  

The structure’s oscillations are described in Eq.4 by Hamilton Variation principle,

\[
\int_{t_1}^{t_2} \delta (W_F - W_k) dt = 0
\]  

Where \(W_F\) and \(W_k\) are total potential energy and total kinetic energy respectively.
Solutions on fluid and structure domains are to be coupled at the fluid structure interface, $I_{FS}$, by setting up kinematic and dynamic constraints Eq. 6&7, in order to simulate the overall dynamics of the fluid conveying tube.

$$v_F(x, t) \big|_F = v_F(x, t) \big|_S$$  \hspace{1cm} (6)

$$u_s(x, t) \big|_s = u_s(x, t) \big|_F, \ x \in I_{FS}(t)$$  \hspace{1cm} (7)

3. Results and Discussion

3.1 Comparison between model predictions and experimental data

The model solutions for different mass flow rate of gas-liquid two-phase flow are compared against the reference values obtained from the experimental single-phase water flow. The relative error is defined as

$$E_R = \frac{m_{Mod} - m_{Ref}}{m_{Ref}} \times 100\%$$

which is used to study the performance of the CFD model. The relative errors of two-phase computations, two-phase experiments, and single-phase numerical model are plotted in Fig 2. For two-phase flow experiment and simulation models, the injected gas flow rate is fixed at 10 l/min at 6 bar and room temperature 23 °C.

Good agreement was found between computed and experimental results, as shown in Fig. 2. It is mainly due to the fact that a two-way coupling interaction between the fluid flow and oscillating tube was applied to the model, where the two-way FSI optimally describes all forces involved in CMFs’ operations [5]. Furthermore, it was found that the experimental results are over-estimated at low mass flow rates and under-estimated at high mass flow rates as those compares to the experimental results for single phase water flow. It may be affected by distribution pattern of gas bubbles and the corresponding flow regimes on measurement on gas-entrained flows. At low flow rates, the oscillations cohere with oscillations of the fluids-conveying tube, and resonance occurs to increase overall amplitude and exaggerate tube deformation. Hence the overrated time shifts and mass flow rates increase.

Fig. 2 Model validation- error on mass flow rate

3.2 Discussion on effects of GVF and differential pressure

To investigate the influence of quantity of gas on the accuracy of CMF performance, the variation of error is presented for variable Gas Volume Fraction (GVF) with the water mass flow rate at 300 kg/min and gas flow rate from 3 to 10 l/min, as shown in Fig.3. The magnitude of error monotonically grows from 0.36% to 1.61% on experimental measurements and from 0.37% to 1.56% on computational results.

In the fluid-conveying tube, the gas bubbles mixed with water induced the mixture density that is less than the density of water. Higher GVF will result lower inertia force the fluid exerts on the meter and the larger meter distortion and hence leading the CMF to under-estimate the mass of the mixture. It is noting that CMFs estimate the mass flow rate from deformation of oscillating the meter tube. However,
gas bubbles have very insignificant effect on the measurement of the reference balance. As a result, CFMs readings remain lower than the balance measurements.

![Graph showing variation of error on mass with increasing gas-volume fraction.](image)

**Fig. 3.** Variation of error on mass with increasing gas-volume fraction.

**SUMMARY**

A combined approach to study the performance of Coriolis Mass Flowmeters on gas-liquid two-phase flow were conducted via experiments and CFD simulations. The numerical model was developed based on a two-way FSI including the interaction between the fluid and structure domains. The numerical model was validated against experimental results. It was found that the measurement error was mainly dominated by GVF in gas-liquid mixture. Drop of mixture’s density associated with GVF rise and gas bubble distribution will influence CMFs error for measurement on gas-liquid two-phase flow.

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