Reducing Phase Decoupling Errors of Coriolis Flowmeters for Slurry Flow Measurement Through Analytical Modelling

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***Abstract*— Phase decoupling is a main source of error that Coriolis flowmeters experience in slurry (liquid-solid) flow measurement. This study proposes an analytical model to estimate and mitigate this error for two-phase slurry flow measurement. The proposed model is developed based on the existing "Bubble theory", where the most significant forces act on solid particles while flowing through a Coriolis tube are studied. Based on the force analysis a modified decoupling ratio equation is proposed. Extensive experimental tests were carried out on a slurry flow test loop to evaluate the performance of the proposed model for mass flowrates ranging from 5435 – 18582 kg/h and Solid Volume Fractions from 0 to 3.3%. In this study, two Coriolis flowmeters are tested on a horizontal pipe section with their measuring tubes in upward and downward orientations. The flowmeters are installed in these ways to examine the effect of flowmeter tube geometry and orientation conditions on slurry flow measurement. Negative errors (up to -3.4%) were observed under both orientations, which agree with the theoretical analysis of decoupled motions between solid and liquid phases. Experimental results revealed that the proposed analytical model yields a relative error within ±1.1% and ±1.3% for upward and downward installations of the two flowmeters, respectively, under all test conditions.**

Keywords—Coriolis flowmeter, multiphase flow, Slurry flow measurement, decoupling error.

I. INTRODUCTION

Coriolis flowmeters are widely deployed for single phase flow measurements in a wide range of industrial sectors. It is one of the most accurate single phase flowmeters, however, the meter performance in terms of measurement errors degrades significantly for multiphase flows [1]. Multiple sources lead to errors, including phase decoupling [2], compressibility [3], asymmetric damping [1], [4] and irregular velocity profile [5]. Extending the applicability of Coriolis flowmeters for multiphase flow metering has received considerable attention in recent years. However, very few studies have been reported regarding the applications of Coriolis flowmeters for slurry flow measurement. Slurry is a mixture flow with solid particles suspended in a liquid and is widely deployed to transfer bulk solids by means of a carrier liquid, for example, paper pulp, coal-water slurry, drilling mud and clays. Worldwide there are many industries which use pipeline transportation of slurry due to its economic advantages [6]. The physical characteristics of slurry flow depend on several factors, including size, density, distribution of solid particles in the pipe as well as the diameter and orientation conditions of the pipe [7]. Moreover, in a slurry flow, the two phases (liquid and solid) interact with each other in the pipe, which significantly affects the behaviour of the mixture [8]. For these reasons, slurry is regarded as a complex flow and its measurement has attracted considerable attention in the global flow measurement research community. There are some studies where Coriolis flowmeters have been applied for hydrate slurry flow metering [9] or the erosive wear of Coriolis tubes due to abrasive properties of slurry has been investigated [10]. Disappointingly, these studies did not include information about the errors of the Coriolis flowmeters tested for slurry flow measurement. One of the recent studies has shown that the phase decoupling effect [2] is the most significant source of error in slurry flow metering [11].

The phase decoupling error arises due to the decoupled motion between multiple phases inside a Coriolis oscillating system. A theoretical treatment of this error is based on the "Bubble theory" [12]. This theory calculates the forces that a fluid-filled oscillating container experiences due to entrained particles, where the particles can either be solid or liquid or gas bubbles. Theoretical investigations of the "Bubble theory" are discussed in [2], [12]. Although these studies theoretically explain the decoupling effect and provide treatment for the error, including slurry flow measurement, they lack practical implementation.

This study aims to reduce the phase decoupling error of Coriolis flowmeters for slurry flow measurement by theoretically and practically examining this error and by analytical modelling. There has been limited literature in this area of research. In this study, a mathematical model is developed to estimate and compensate for the phase decoupling error of Coriolis flowmeters while measuring slurry flow. This model analyses the forces that act between solid and liquid phases while flowing through Coriolis tubes and generates a decoupling ratio to mitigate the error. The performance of the proposed model is then assessed through a series of experimental tests on a purpose-built slurry flow test loop under a range of conditions. The effect of flowmeter tube geometry and orientation conditions on measurement errors is practically examined by testing Coriolis flowmeters in upward and downward installations. The original errors along with the additional factors that lead to the errors including density difference are presented.

II. METHODOLOGY

A. Measurement principle

The principle of the proposed system for slurry flow metering with a Coriolis flowmeter is shown in Fig. 1. The flowmeter provides apparent mass flowrate and apparent density readings of the mixture in the pipe [1]. Although for two-phase conditions these readings are erroneous, they still reflect the true mass flow rate and SVF of the mixture [11]. The proposed analytical model that is based on force analysis is then performed to estimate the decoupling ratio. Later, the decoupling ratio is incorporated in Coriolis flowmeter readings to estimate and mitigate measurement errors while determining the mass flowrates of slurry.

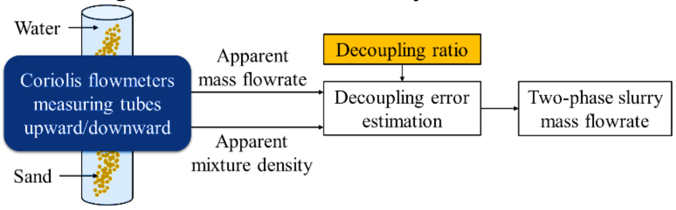


Fig. 1. Principle of the slurry flow metering system

B. Quantification of phase decoupling effect

The term phase decoupling describes the phenomenon when a Coriolis flowmeter handles two phases (i.e., solid particles or gas bubbles entrained into liquid), the second phase cannot exactly follow Coriolis oscillation. For two-phase flow, the differences in phase density result in different accelerations along the Coriolis oscillation direction. Consequently, the induced vibration amplitudes of the two phases become different. As a result, the phase decoupling effect would cause some part of the mass of inertia not sensed by the Coriolis measuring tube(s) and thereby lead to an underestimation of mixture mass flowrate and density [2], [12].

In order to mathematically quantify the phase decoupling effect, the following assumptions are made in this study:

- The liquid and entrained solid particles are assumed to be incompressible.
- The Coriolis tubes are spacious enough to accommodate the motion of particles.
- The entrained solid particles are spherical in shape and uniformly distributed along Coriolis tubes.
- Particles are assumed to experience rectilinear motion along the Coriolis oscillation direction and no contact between the adjacent spheres nor tube wall.

These assumptions are also stated in the Bubble theory and they are achievable for SVF up to 10% [2], [12]. This in turn indicates the proposed model can be applicable for SVF up to 10%. In order to quantify the decoupling effect, a quantity known as the decoupling ratio (R_d) is defined:

$$R_d = \frac{v_s}{v_l} \tag{1}$$

Here, v is velocity and subscripts l and s denote liquid phase and entrained spheres/solid particles, respectively. R_d is then gained by analysing the forces that act between the liquid and solid phases inside the Coriolis tubes.

C. Force analysis

In a Coriolis oscillation system, when solid particles are suspended into liquid there are certain forces that act on the particles. Among them, buoyancy-like force (F_B) and added mass force (F_A) are the most significant force terms [2]. Therefore, in this study, the total force (F_T) that acts between particles and liquid inside a Coriolis oscillation system is obtained by taking a summation of F_B and F_A:

$$F_T = F_B + F_A \tag{2}$$

- **Total force:** The total force is defined by Newton's second law of motion:

$$F_T = m_s \frac{d}{dt} v_s \tag{3}$$

$$F_T = \rho_s V_s \frac{d}{dt} v_s \tag{4}$$

where, m_s, ρ_s, V_s and dt represent the mass, density, volume of solid particles and change in time, respectively. The volume of solid spheres is defined in Eq. (5), where, r is radius.

$$V_s = \frac{4}{3}\pi r^3 \tag{5}$$

- **Buoyancy-like force:** This force arises due to pressure difference induced by the acceleration of surrounding liquid. Driven by the Coriolis oscillation, when a solid particle enters the tube, it experiences less acceleration than the liquid since solids are typically heavier [3]. For example, if the tube is driven upwards, the solid particles would initially move downwards with respect to the liquid and then upwards.

The buoyancy force is defined by:

$$F_B = \rho_l V_s \frac{d}{dt} v_l \tag{6}$$

where, ρ_l is the density of the liquid phase.

- **Added mass force:** For spherical particles, the definition of added mass force is half of the mass of liquid displaced by the particle [2]. This force exists because the particles have to displace some volume of the surrounding liquid. The relative motion of particles against surrounding bulk liquid while constantly displacing fluid will lead to an acceleration of the nearby bulk liquid and result in an additional reactive force [5].

The added mass force is defined by:

$$F_A = C_a \rho_l V_s \frac{d}{dt}(v_l - v_s) \tag{7}$$

where, C_a is the Stokes' drag coefficient and it is 0.5 for spherical shaped particles [2].

Although, Eq. (7) is applicable for mixtures where entrained particle density is significantly lower compared to liquid density i.e. air-water two phase flow. In case of slurry flow, it is no longer applicable and the main reason is density difference. Gas-bubbles density (i.e. air ~1.5 kg/m^3) is significantly lower than liquid density (i.e. water ~998 kg/m^3). Whereas, the density of solid particles (i.e. sand > 2000 kg/m^3) is higher than liquid (typically). Unlike gas-liquid flow where the gas phase is lighter and moves faster than liquid [2], [5], solid particles are heavier and move less distance along the Coriolis oscillation direction and have relatively lower velocity compared to liquid. It is for these reasons the resulting acceleration of the solid phase is smaller in slurry compared to the gas phase in gas-liquid flow. Therefore, the decoupling effect under gas-liquid and solid-liquid two-phase flow conditions would also be different. Consequently, the decoupling ratio equations are different.

As a result, this study proposes an amended version of the existing decoupling ratio equation for two-phase slurry flow measurement. Instead of only considering the force that the liquid phase exerts on solid phase, the force that the solid particle applies to the liquid is also considered and the remaining force is used to develop the decoupling ratio equation. Where, F_R is termed as the remaining force:

$$F_R = C_a(\rho_s - \rho_l)\, V_s \frac{d}{dt}(v_l - v_s) \tag{8}$$

Finally, the force analysis is then done by substituting Eq. (4), (6) and (8) into Eq. (2).

$$\rho_s V_s \frac{d}{dt} v_s = \rho_l V_s \frac{d}{dt} v_l + \frac{1}{2}(\rho_s - \rho_l) V_s \frac{d}{dt}(v_l - v_s) \tag{9}$$

The decoupling ratio is then determined by solving Eq. (9) for the velocity ratio of solid and liquid phases.

$$R_d = \frac{v_s}{v_l} = \frac{\rho_s + \rho_l}{3\rho_s - \rho_l} \tag{10}$$

From Eq. (10) it is evident that decoupling ratio is entirely dependent on liquid and solid phase densities.

D. *Estimation of errors due to phase decoupling effect*

Attributable to the decoupling effect, the apparent (observed) mass flowrate “felt” by the Coriolis flowmeters is expressed by:

$$\dot{m}_d = \frac{d}{dt}\left(\rho_s A_t R_d \alpha_s + \rho_l A_t (1 - R_d \alpha_s)\right) \tag{11}$$

The actual mass of the mixture flowing through Coriolis flowmeter, without decoupled motions between different phases is:

$$\dot{m}_e = \frac{d}{dt}\left(\rho_s A_t \alpha_s + \rho_l A_t (1 - \alpha_s)\right) \tag{12}$$

Here, $\dot{m}_d$ and $\dot{m}_e$ refer to mass flowrates sensed by Coriolis flowmeters with and without decoupling effect, respectively. A_t is the cross-sectional area of Coriolis tube and α_s denotes SVF, which is defined as

$$\alpha_s = \frac{\rho_m - \rho_l}{\rho_s - \rho_l} \times 100\% \tag{13}$$

Here, ρ_m is the Coriolis flowmeter’s mixture density reading.

The relative error in the mass flowrate measurement ($E_{d\dot{m}}$) due to phase decoupling is then calculated by:

$$E_{d,\dot{m}} = \frac{\dot{m}_d - \dot{m}_e}{\dot{m}_e} \times 100\% \tag{14}$$

By combining Eq. (11), (12) and (14) the measurement error is defined as:

$$E_{d,\dot{m}} = \frac{(\rho_s - \rho_l)\alpha_s (R_d - 1)}{\rho_s \alpha_s + \rho_l (1 - \alpha_s)} \times 100\% \tag{15}$$

III. Experimental Results and Discussion

A. *Experimental test conditions*

The experimental data in this study were acquired from a sand-water slurry flow test loop (laboratory-scale 50 mm bore). Figs. 2 and 3 show the schematic and photo of the test loop, respectively. The key elements of the rig consist of two Coriolis flowmeters, a mixture tank (1500 litres), a weighing tank (300 litres), a weighing scale (with uncertainty lower than the Coriolis flowmeters), a main pump (centrifugal, rated 5.5 kw), an agitator (0.37 kw) and two motor control inverters. The two Coriolis flowmeters are installed with their measuring tubes in up and down directions. These two orientations are used to investigate the effects of Coriolis tube geometry and orientation conditions while measuring slurry flow. The main pump, flowmeters and mixture tank are connected through a main circulation loop. The mixture tank is used to store sand-water mixture whilst an agitator on top of the mixture tank serves to create dilute sand-water slurry in the test section. The slurry flows through the test loop via the main pump. To control the direction of slurry flow several valves are fitted. The reference mass flowrate of slurry is acquired through a weighing system (the weighing tank over the weighing scale). The desired mass flowrates and SVFs of this study are achieved by controlling the frequencies of main pump and agitator inverters, respectively.

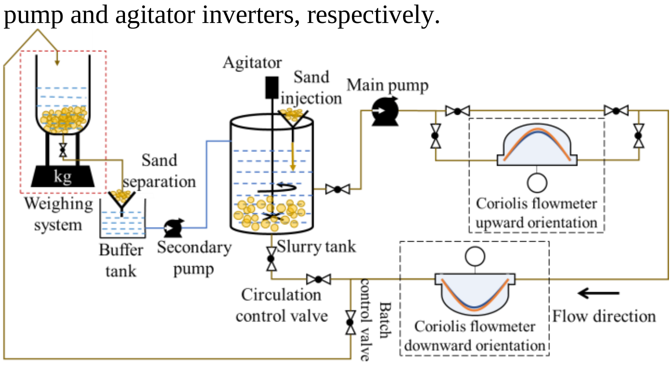


Fig. 2. Slurry flow test loop [11].

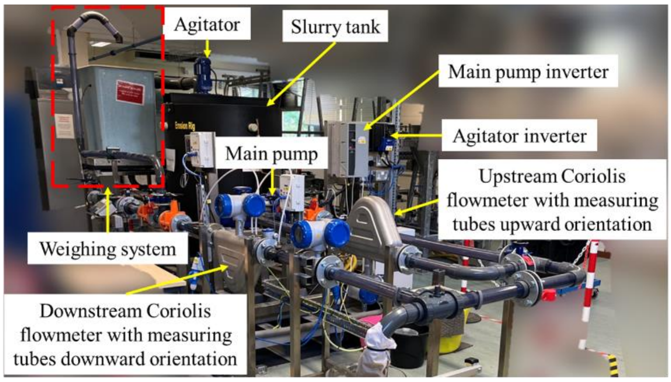


Fig. 3. Photo of the slurry flow test loop [11].

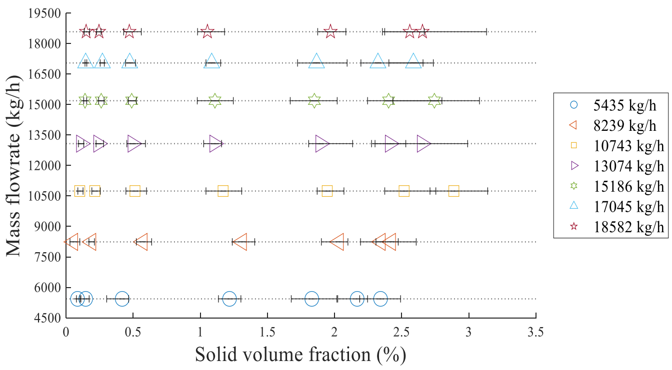
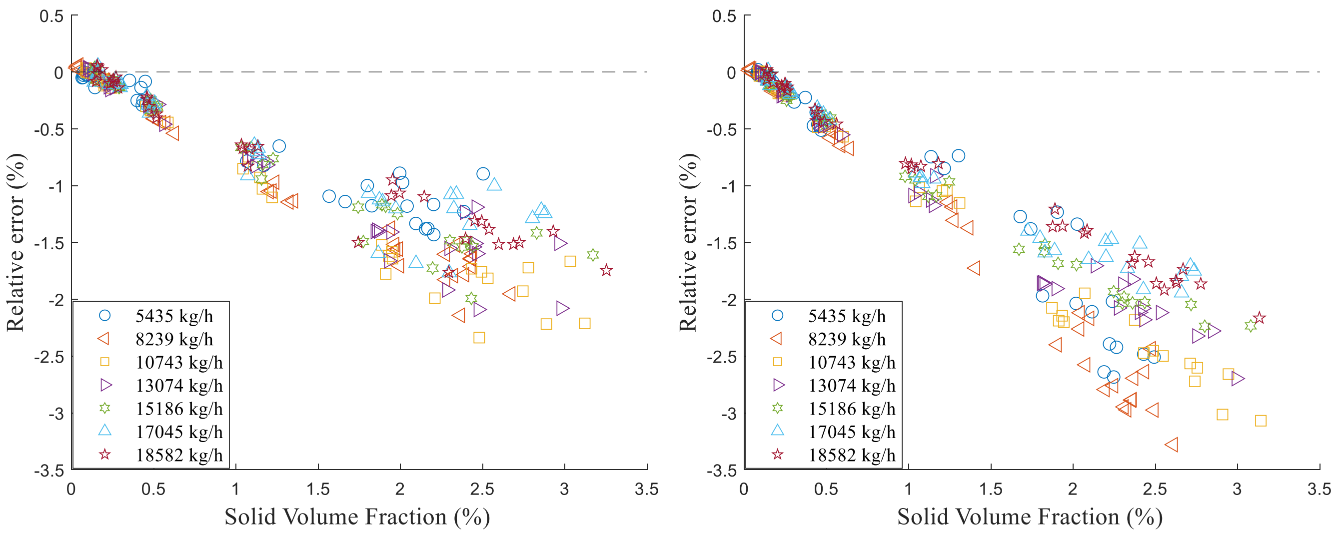


Fig. 4. Test matrix.

Fig. 4 illustrates the test matrix, which consists of seven different mass flowrates (5435, 8239, 10743, 13074, 15186, 17045 and 18582 kg/h) over SVF 0-3.3%, with sand particle size ranges between 150 – 300µm. The measurements under each test condition were repeated five times. The horizontal bars represent the minimum, maximum and average spreads of SVFs for their respective mass flowrates. Since slurry is flown in a circulation loop, mass flowrates also has an effect on SVFs thereby comparatively higher SVF spread is observable for high mass flowrates. In this study, the apparent mass flowrates are obtained from Coriolis flowmeter readings and the reference mass flowrates are obtained by dividing the weighing scale reading by operating time. The original errors of Coriolis flowmeters while measuring slurry flow are determined by substituting $\dot{m}_d$ and $\dot{m}_e$ with apparent and reference mass flowrates in Eq. (14), respectively.

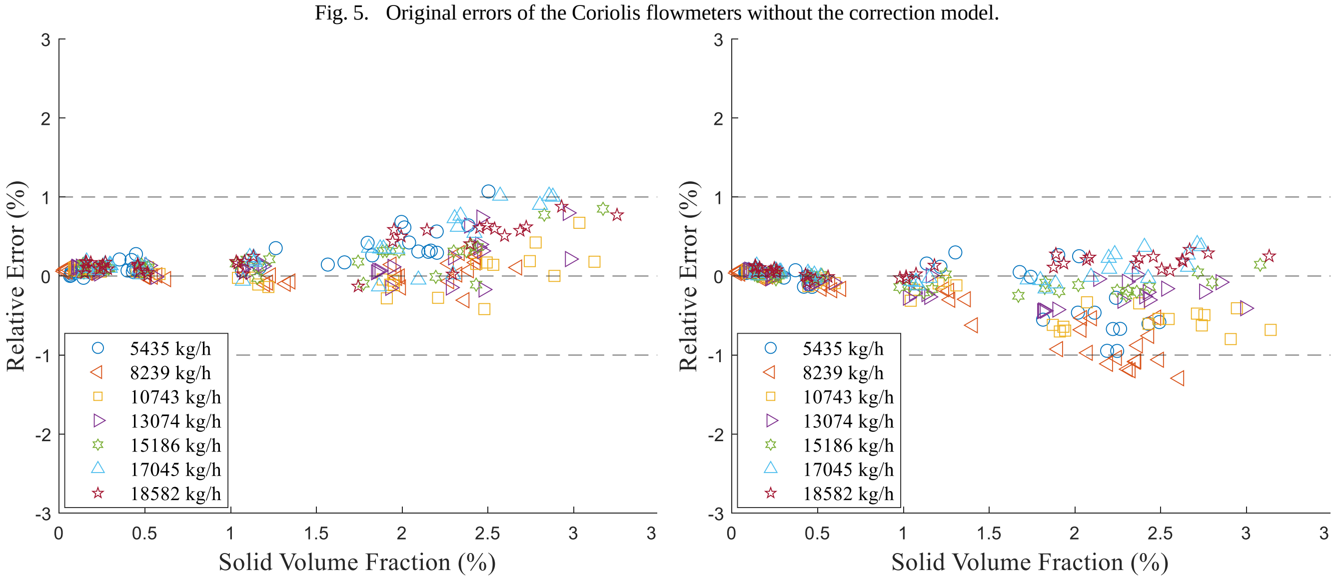
B. *Analysis of original errors*

The original errors of the two Coriolis flowmeters are shown in Fig. 5. Majority of the errors are negative, confirming that the phase decoupling effect is the main source of error. Moreover, a clear relationship exists between the errors and SVF, with higher SVF corresponding to larger errors. Furthermore, the downward meter's worst error (-3.4 %) is greater than that of the upward one (-2.4 %). This is due to sand particles accumulation inside the downward meter's tubes, which affects the density measurement of the flowmeter. On the other hand, this accumulation of sand occurs at the inlet side of upward meter tubes. Therefore, the downward flowmeter experiences higher slurry density compared to upward flowmeter at the initial state of flow. Consequently, the downward flowmeter experiences additional negative errors. This phenomenon is also referred to as asymmetric damping [4]. The effect of asymmetric damping is significant for low flowrates, particularly for the downward meter, as larger errors are observed for mass flowrates 5435 and 8239 kg/h. Another potential cause of error could be imbalance, which occurs when the mixture flow is not divided equally between the two measuring tubes. It is evident that, in addition to density differences between multiple phases, the geometry and installation orientations of measuring tubes have the potential to impact the behaviours of Coriolis flowmeters. As a result, it is advantageous to measure the mass flow rate of slurry with a Coriolis flowmeter in upward orientation as opposed to downward orientation.



(a) Measuring tubes upward (b) Measuring tubes downward

Fig. 5. Original errors of the Coriolis flowmeters without the correction model.



(a) Measuring tubes upward (b) Measuring tubes downward

Fig. 6. Error in slurry flow measurement with the correction model.

C. *Slurry mass flowrate correction*

The proposed analytical model is implemented to estimate the errors illustrated in Fig. 5. In this study, the average sand density is found to be 2680 kg/m^3. The water density (~998 kg/m^3) is determined through current process temperature readings of Coriolis flowmeters using the IAPWS R7-97 method [13]. The decoupling ratio is then determined through

Eq. (10). The average phase decoupling ratio that is used in this study is 0.52. Finally, the decoupling ratio along with sand and water densities as well as SVFs are then applied to Eq. (15) in order to estimate the mass flowrate measurement errors of Coriolis flowmeters for slurry metering. To determine the intended mass flowrates of slurry, the estimated errors are then combined with the apparent mass flowrate readings of corresponding Coriolis flowmeters. The relative errors of the proposed correction model are shown in Fig. 6. It is clear that the proposed model is able to estimate the flow measurement errors. Throughout the test conditions, the errors are within ±1.1% and ±1.3% for the two installation orientations, respectively. For low mass flowrates (5435 and 8239 kg/h) the proposed model errors are slightly higher than ±1% for SVF ~2.5%, as for these conditions the flowmeters experience asymmetric damping errors in addition to phase decoupling errors.

The model proposed in this study is simple to implement to reduce the measurement errors of Coriolis flowmeters due to phase decoupling effect. The benefit of using the analytical modelling approach is that the measurement errors can be corrected based on the apparent mass flowrates and density readings (internal parameters) from Coriolis flowmeters along with other prior information (e.g. liquid and solid density), without using additional instrumentation for providing references.

IV. Conclusion

This paper has presented an analytical model to estimate and compensate for the phase decoupling errors of Coriolis flowmeters for slurry flow measurement. The proposed model of this study provides a deeper understanding of the decoupled motion between multiple phases in a Coriolis oscillating system while measuring slurry flow. This study highlights the importance of density difference between multiple phases in reducing phase decoupling errors.

- The experimental results have revealed that the phase decoupling effect is the most significant source of error in slurry flow metering, as negative errors (ranging from 0 to −3.4%) are observed for the majority of experimental data.
- The results have also shown that a Coriolis flowmeter in an upward installation performs better than downward installation. As larger errors are observed from the downward meter and the underlying reason is found to be the asymmetric damping.
- For low mass flowrates, the impact of asymmetric damping is relatively large, particularly for the downward meter. This indicates that mass flowrate also affects the behaviour of Coriolis flowmeters while measuring slurry flow.
- The proposed model reduced the original measurement errors to ±1.1% and ±1.3% for upward and downward installations, respectively, under all test conditions.
- The existing analytical model is suitable for mixtures where the density of entrained particles is lower than the liquid density, such as air-water mixtures. However, in the case of slurry, the model needs to consider the force applied by the solid particles to the liquid to develop an effective decoupling error compensation model.

Efforts will be made in the future to practically examine the effects of asymmetry and damping on slurry flow metering.

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