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Predicting the Output Error of a Coriolis Flowmeter under Gas-Liquid Two-Phase Conditions through Analytical Modelling

J.Liu[1,2], T.Wang[1,2], Y.Yan[1], X.Wang[3]

[1]School of Engineering and Digital Arts, University of Kent, Canterbury, Kent CT2 7NT, U.K.
[2]KROHNE Ltd., Wellingborough NN8 6AE, U.K.
[3]School of Mathematics, Statistics and Actuarial Science, University of Kent, Canterbury, Kent CT2 7FS, U.K.
E-mail (corresponding author): Y.Yan@kent.ac.uk

Abstract

Coriolis flowmeters are recognised to give excellent performance of the mass flow measurement and independent density measurement of single-phase flow. However, the large measurement error of a Coriolis flowmeter under gas-liquid two-phase flow conditions makes it unsuitable for many industrial processes where gas-liquid two-phase flow is encountered. Although analytical models have been proposed to explain the reasons behind the large output error of a Coriolis flowmeter under two-phase conditions, none of the individual theories nor their combinations can match experimental results to within 10% difference. In particular, when the gas volume fraction (GVF) exceeds 15%, the existing analytical models are not suitable. In this paper, a semi-empirical analytical model is established by combining existing analytical models with empirical terms and coefficients. The applicable range of this new analytical model is now extended to up to 40% GVF, which also better matches the experimental results. Comparisons between the modelling predictions and the experimental results for air-water two-phase flow on a two-inch Coriolis flowmeter (KROHNE OPTIMASS 6000) are made. Comparisons indicate that 2314 out of 2457 (94.2%) modelling predictions in mass flowrate fall within 10% relative error while 2403 out of 2457 (97.8%) predictions in GVF measurements fall within 5% absolute error. The outcome of this research contributes to an analytical approach to predict output error of Coriolis flowmeters under gas-liquid two-phase flow with improved accuracy and extended GVF range.

1 Introduction

Gas-liquid two-phase flow is commonly encountered in many industrial processes due to production requirement or inevitable gas entrainment from various sources. For the purposes of reducing cost, improving safety or meeting legal requirements, accurate mass metering of liquid flowrate is important but challenging to achieve under complex two-phase flow conditions.

There are many approaches to address the challenges of gas-liquid two-phase flow [1]. Phase fraction measurement techniques (e.g. electrical impedance/capacitance tomography or absorption of an electromagnetic wave such as gamma ray, X-ray microwave, infrared etc.) and phase velocity measurements (e.g. cross-correlation, Venturi) are often combined to work out the flowrate and concentration of each phase. Also, recently developed Magnetic Resonance flowmeter can achieve 3% to 5% uncertainty in volumetric measurements of liquid phase and 8% to 10% uncertainty in volumetric measurements of gas phase [2]. However, these multi-phase flowmeter solutions could be expensive to own and maintain and not suitable for applications where single-phase can be expected for most of the time. Coriolis flowmeters as the most accurate single-phase mass flow metering devices may be an ideal candidate to address the gas-liquid flow measurement problem owing to its direct mass flow measurement and multivariable sensing nature. Recent advances in digital converters allow a Coriolis flowmeter to maintain working status and produce repeatable erroneous outputs [3], which clearly indicate additional physical interactions between the gas-liquid flow and the fluid conveying tube. Despite extensive investigations into the performance of Coriolis flowmeters under two-phase flow conditions, neither existing analytical models nor their combinations can match the experimental results [4] especially when the GVF is larger than 15%.

In this paper, we proposed a novel semi-empirical analytical model that agrees with the experimental results to within a relative error of $\pm$10% for mass flowrate and an absolute error of $\pm$5% for GVF measurements. After investigating the behaviours of a two-inch bent-twin-tube Coriolis flowmeter under a wide range of GVF, flowrate and flow regimes [4], error terms from existing analytical models with correction factors as well as new error terms are used to predict the mass and density measurement errors of the Coriolis flowmeter.

2 Methodology

Firstly, the existing analytical models for decoupling and compressibility error of the Coriolis flowmeter under gas-liquid two-phase conditions are reviewed. Secondly, invalidity of the assumptions for such models under higher GVF is discussed. Thirdly, correction of existing error terms and additional error term to extend the applicability of the analytical models are described to predict the behaviours of the Coriolis flowmeter under gas-liquid two-phase flow.

2.1 Review of existing analytical models

There are two quantified analytical models available in the literature to describe the behaviours of the Coriolis flowmeter under gas-liquid two-phase flow, namely, decoupling error and compressibility error.

Decoupling, as a decoupling error, refers to the relative motion of gas bubbles and their surrounding liquid in the transverse direction during vibration. As it is derived in [5], the gas bubbles travel further than the surrounding liquid, resulting in a small portion of the liquid not fully coupled with the tube and therefore have less inertia sensed by the Coriolis tubes. Consequently, decoupling error leads to under-read of mass flowrate and density as shown in equations below [4]:

$$E_{d,q_m} = \frac{1-F}{1-\alpha}\,\alpha \tag{1}$$

$$E_{d,\rho} = -F\,\alpha \tag{2}$$

where E is the relative error, F is decoupling ratio between gas and liquid phases, and α is cross-sectional void fraction of the pipe (in this paper we assume α = GVF as the slip ratio of homogeneous gas-liquid mixture is negligible for the accuracy of the proposed analytical model). Subscription d, q_m, and ρ are decoupling error, mass flowrate, and density, respectively.

Compressibility, as its name implies, describes the deformation of the gas-liquid mixture inside the vibration tube of a Coriolis flowmeter. Although a number of formulas from different papers [6]–[9] have been used to describe the compressibility error depending on the complexity of the model, the compressibility error in its simplest form is used in this study to the accuracy we are working at.

$$E_{C,q_m} = \frac{1}{2}\left(\frac{\omega}{c}b\right)^2 \tag{3}$$

$$E_{C,\rho} = \frac{1}{4}\left(\frac{\omega}{c}b\right)^2 \tag{4}$$

where c, ω, and b are mixture speed of sound, tube vibration frequency and tube radius, respectively. Subscription C is compressibility error. Consequently, compressibility error leads to over-read of mass flowrate.

2.2 Problem in existing analytical models

Since the existing analytical models are restricted by various assumptions, they do not work at GVF larger than 15%. This GVF limit is inferred from the publications that reports the agreement between existing analytical models and experimental results up to 15% (Tables 1 and 2 from [9]). It is also confirmed from the experimental data from this work that the existing analytical model only work for GVF up to 5% (as demonstrated in Figure 1). Two main assumptions from existing analytical models are:

- No interactions among bubbles nor between bubbles and pipe wall are assumed for decoupling error model.
- The gas-liquid fluid is assumed to be a homogeneous mixture for compressibility error model.

When the number and size of bubbles increase with GVF, both assumptions are no longer valid. As a result, the decoupling ratio calculated from the analytical model will not be accurate. Similarly, when GVF increases, the gas phase will decouple from the liquid phase and therefore the mixture is no longer homogeneous. Therefore, the compressibility error from the model will not be accurate.

There are also other factors not quantified such as imbalance, asymmetry distribution of bubbles and different geometry of the fluid conveying pipe. For the most common Coriolis flowmeters which have a twin tube in structure, gas bubbles could be unevenly distributed in the tubes. Such uneven distribution results in imbalance which increase mechanical disturbances in the vibration signal. In addition, owing to the pressure drop or difference in gas distribution upstream and downstream of the same tube, mechanical disturbances can also be expected. Last but not the least, the analytical models are derived for Coriolis flowmeters with straight tubes whereas those with bent tubes are commonly used nowadays for their structural advantages (e.g. higher measurement accuracy under a wider range of temperature and more flexible resonance frequency design). Because of all the reasons above, neither existing analytical models nor their combinations can predict the errors of Coriolis flowmeter under gas-liquid two-phase conditions to an acceptable accuracy, especially when the GVF is higher than 15%.

2.3 Improvements of existing analytical models

2.3.1 Improvements on decoupling error prediction

According to the analytical model in [5], a decoupling ratio can be calculated based on the properties of the gas and liquid phases including densities, viscosities, bubble sizes and vibration frequency. However, this would only work when no bubble to bubble or bubble to wall interaction is assumed. When bubble to bubble or bubble to wall interaction are expected, which usually happen under higher GVF, the gas would not be able to decouple from the liquid as far as calculated. In order to account for the reduced decoupling ratio caused by the interactions, the term related to GVF is introduced to account for the bubble to bubble and bubble to wall interaction while an empirical coefficient is introduced so that the output of the model matches with experimental results. The corrected decoupling ratio F' is shown as follows:

$$F' = C_F F(1-\alpha) \tag{5}$$

where C_F is an empirical coefficient, which has a value of 0.854, determined from the experimental results. The derivation is stated in Section 3.2.

As a result, the corrected decoupling error from Equations (1) and (2) by substituting decoupling ratio F with F' becomes:

$$E'_{d,q_m} = \frac{1-F'}{1-\alpha}\,\alpha \tag{6}$$

$$E'_{d,\rho} = -F'\,\alpha \tag{7}$$

2.3.2 Adding damping term

In addition, over-reading of the Coriolis flowmeter due to compressibility or similar principle is caused by larger damping under two-phase conditions compared with single-phase flow conditions. Additionally, flowrate also affects the over-reading of the Coriolis flowmeter according to experimental results [4]. Therefore, an additional term combining damping and flowrate is added to the prediction of the output of the behaviours of the Coriolis flowmeter as shown below:

$$E_E = C_E\, G_D\, \alpha_{q_m} \tag{8}$$

where C_E is an empirical constant with a value of 1.8 derived from the experimental results (Section 3.2). G_D is the normalized drive gain and α_{qm} is the normalised mass flowrate of the flowmeter, respectively as shown in equations below:

$$G_D = \left(\frac{V_d}{(V_A+V_B)/2} - G_{D0}\right) \times 100\% \tag{9}$$

where G_{D0} is the drive gain of the Coriolis flowmeter measured when the fluid conveying tube is filled with water under no flow conditions.

$$\alpha_{q_m} = \frac{q_m}{q_{m,n}} \times 100\% \tag{10}$$

where q_m and $q_{m,n}$ are reference flowrates of the liquid phase and nominal flowrate of the meter under test, respectively.

2.3.3 Complete Expression of the Improved Model

From the statements above, the prediction on the mass flowrate and density errors are expressed below when the properties of the liquid phase are the measurands:

$$E_{qm} = E'_{d,q_m} + E_{C,q_m} + E_E \tag{11}$$

$$E_\rho = E'_{d,\rho} + E_{C,\rho} \tag{12}$$

3 Experimental results and discussion

3.1 Test facility and test conditions

The experimental setup has been covered in a previously published paper [4] and therefore will not be repeated here. In summary, air-water two-phase tests were conducted on a two-inch bore rig with the Coriolis flowmeter under test (KROHNE OPTIMASS 6000 S50). The test matrix is designed in a way that the behaviours of the Coriolis flowmeter under various gas-liquid two-phase flow test conditions were recorded. The collected data is then used to derive and validate the analytical model proposed from this paper. The covered test conditions are summarised in Table 1.

Table 1: Covered test conditions

Factors	Coverage
GVF	0% to 40%
Flowrate	5000 kg/h to 35000 kg/h
Bubble size and distribution	Different length of upstream straight pipe, different gas injection points, different flow conditioners
Temperature	20 °C and 40 °C
Pressure	0.2 bar and 0.7 bar

Based on the combination of the test variation, 29 data sets with different test conditions are listed in Table 2. Three air injection points (1,2, and 4) are available either from top or bottom of the pipeline. Different flow conditioners are used, which were installed either upstream or downstream (corresponding to @4U and @4D, respectively) of the spool piece directly connected to the upstream flange of the meter under test or installed upstream (corresponding to @2U) of the spool piece directly connected to the upstream flange of the sight glass, as shown in Fig. 2 of [4]. Test temperature was controlled to be either 20 °C or 40 °C and back pressure was controlled to be either 0.2 bar or 0.7 bar.

Table 2: Test conditions

Data Sets	Injection Location	Flow conditioners	Temperature (°C)	Pressure (bar)
data01	1 bottom	Hybrid@2U	20	0.2
data02	1 bottom	Hybrid@4U	20	0.2
data03	1 top	Grid@4D	20	0.2
data04	1 top	Hybrid@2U	20	0.2
data05	1 top	Hybrid@4U	20	0.2
data06	2 bottom	Hybrid@2U	20	0.2
data07	2 bottom	Hybrid@4U	20	0.2
data08	2 top	Hybrid@2U	20	0.2
data09	2 top	Hybrid@4U	20	0.2
data10	1 top	no	20	0.2
data11	1 top	no	20	0.7
data12	1 top	no	40	0.2
data13	2 bottom	no	20	0.2
data14	2 bottom	no	20	0.7
data15	2 bottom	no	40	0.2
data16	1 bottom	no	20	0.2
data17	1 bottom	no	20	0.2
data18	2 top	no	20	0.2
data19	4 bottom	no	20	0.2
data20	1 top	no	20	0.2
data21	2 bottom	no	20	0.2
data22	1 top	no	20	0.2
data23	1 top	no	20	0.2
data24	2 bottom	no	20	0.2
data25	1 top	Swirl@2D	20	0.2
data26	2 bottom	Swirl@2D	20	0.2
data27	2 bottom	Grid@2D	20	0.2
data28	1 top	Grid@2D	20	0.2
data29	1 top	Grid@4D	20	0.2

Since there is a large number of test points in all 29 test conditions (2457 test points in total), only representative test sets are selected to demonstrate the problems in existing analytical model and to illustrate the development and validation of the analytical model. In this case, data 13 is selected as one of the datasets that best fits the analytical model while data 5 is selected as one the few datasets that worst fits the model.

3.2 Comparison of experimental results with model predictions

Figure 1 shows the comparison between the experimental results and predictions using existing analytical models.

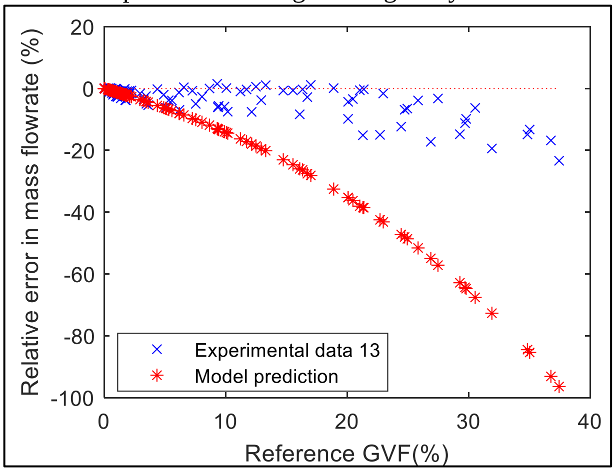

Figure 1 Comparison between model prediction and experimental results

It can be observed that the existing analytical model can predict the behaviours of the Coriolis flowmeter at very low GVF (up to 5%) and the trend is correct for the remaining GVF sections. However, the prediction error will soon become unacceptable with the increase of GVF. This error in prediction is caused by the overestimated decoupling error. For very low viscosity liquid such as water, the theoretical decoupling ratio approaches 3, which means the gas bubbles travels 3 times further than liquid in the direction of vibration. However, with the increase of GVF, bubbles start to interact with each other and the pipe wall, reducing the actual decoupling ratio. As a result, the decoupling ratio should reduce with GVF, which can be described in Equation (5). The empirical coefficient C_F is determined based on the experimental results of all 29 sets from Table 2. Output prediction using the empirical coefficient is compared with the experimental result and the coefficient that results in the lowest overall difference is found to be 0.854.

In the meantime, the scattered outputs under the same GVF is obtained when the flowrate is different. Neither existing decoupling nor compressibility model take flowrate into consideration as shown in Figure 2.

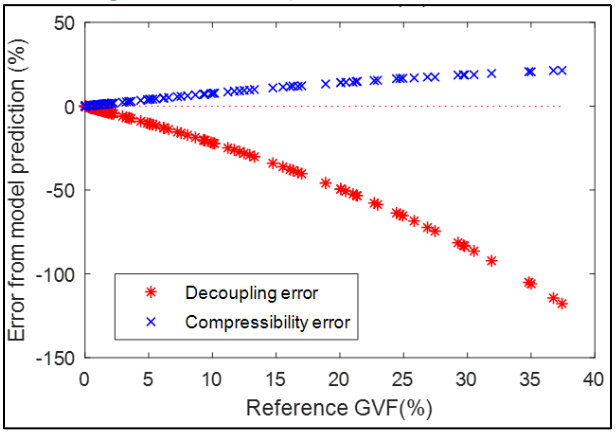

Figure 2 Decoupling error and compressibility error terms

Since the behaviours of the Coriolis flowmeter, especially on the positive error part (as shown in Figure 1) is correlated to flowrate and damping (as shown in Figure 3) during gas-liquid two-phase flow, the error term in Equation (8) is added to the model to better predict positive error together with the compressibility error while reflect the error scatter in the experimental data. Similarly, the empirical coefficient C_E is determined through comparison with experimental results, which results in the lowest overall difference.

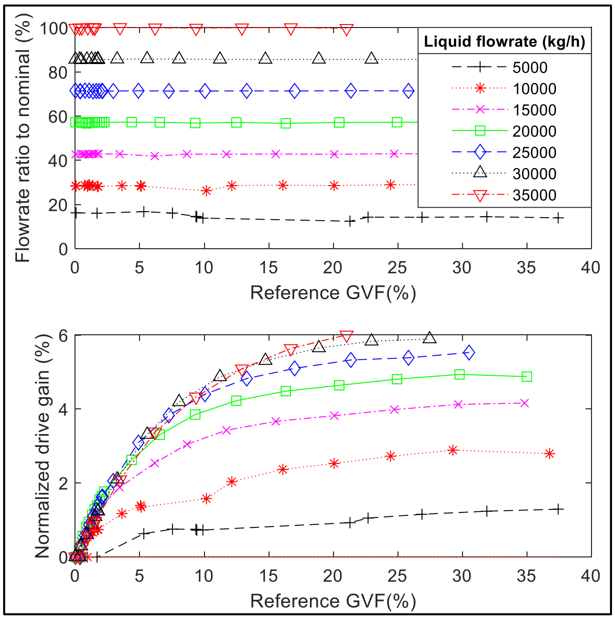

Figure 3 Flowrate and damping plot under different flowrate

The experimental results and the prediction from the improved model are shown in Figure 4.

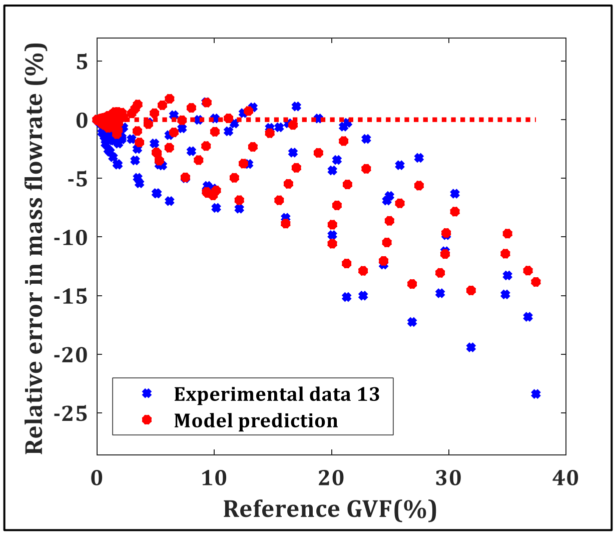

Figure 4 Comparison between improved analytical model (data 13) and experimental results

With the empirical coefficients C_F and C_E, the experimental error can be accurately predicted. The improved physical model predicted that 2314 out of 2457 (94.2%) predictions of mass flowrate fall within 10% error while 2403 out of 2457 (97.8%) predictions of GVF measurements fall within 5% error.

Lastly, example of predictions from the improved analytical model that do not reflect experimental results is shown in Figure 5.

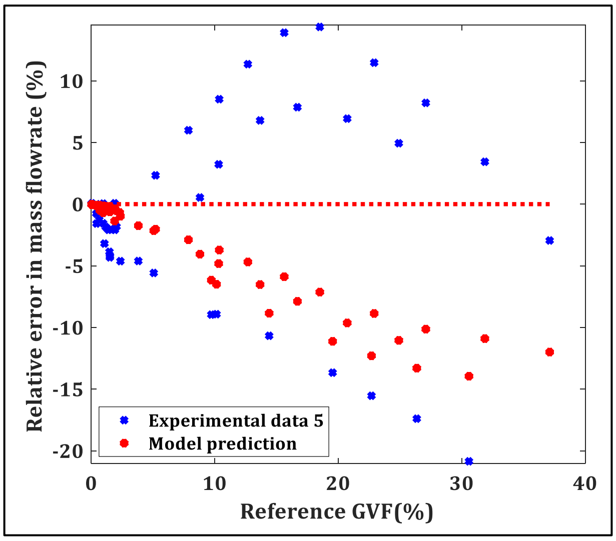

Figure 5 Comparison between improved analytical model (data 5) and experimental results

Such poor predictions of the model occur when the flow conditioner (described in detail in [4]) is either grid mixer or hybrid mixer while installed too near (@4U and @4D) to the meter under test. In these cases, the bubbles are assumed to be smaller since they are broken down by the flow conditioners and have no time to merge back particularly when the flowrate is high. As a result, positive error that larger than model predicted compressibility error occurred in the experiment. A solution to this problem is quite simple. Since such test conditions are deliberately created to investigate the behaviours of the Coriolis flowmeter under various test conditions, it can be simply avoided by not using flow conditioners or using sufficient straight section upstream of the Coriolis flowmeter under test. By allowing sufficient time for the gas bubble to reach equilibrium state, the improved analytical model proposed in this paper can be used to predict the output error of the Coriolis flowmeter.

4 Conclusion

In this paper, an improved analytical model is presented to better predict the behaviours of the Coriolis flowmeter under air-water two-phase flow conditions. According to the comparison between the improved analytical model and experimental results, there are 2314 out of 2457 (94.2%) predictions of mass flowrate that are within 10% error while 2403 out of 2457 (97.8%) predictions of GVF measurements are within 5% error. Such performance is confirmed under a variety of test conditions and the outliners can be easily avoided by not using unusual test setups. By loosening the modelling restrictions, the applicable range of the model is also extended from maximum 15% GVF to at least 40% GVF. By utilising diagnosis signals that are already available from the Coriolis flowmeter, physical interaction inside the Coriolis flowmeter can be better described and predicted with the additional flow condition information. Furthermore, the results demonstrate the possibility of using a Coriolis flowmeter incorporating an analytical model to measure gas-liquid two-phase flow. With further GVF measurement or investigation into the correlation between GVF and mass flowrate errors, the proposed model can lead to solutions that achieve competing performance compared to the radiological measurement systems (3% to 5% uncertainty in volumetric measurements of the liquid phase in [10]) and other complex measurement systems (3% to 5% uncertainty in volumetric measurements of the liquid phase in [2]) under various test conditions. Future work will include the examination of the generalization capability of such an analytical model for Coriolis flowmeters of different size and fluids with different properties.

References

[1] R. Thorn, G. A. Johansen, and B. T. Hjertaker, ‘Three-phase flow measurement in the petroleum industry’, *Measurement Science and Technology*, vol. 24, no. 1, p. 012003, 2013.

[2] A. M. Bilgic, J. W. Kunze, V. Stegemann, M. Zoeteweij, and J. Hogendoorn, ‘Multiphase flow metering with nuclear magnetic resonance spectroscopy’, in *Proceedings SENSOR 2015*, Nürnberg, Germany, 2015, pp. 292–297.

[3] M. P. Henry *et al.*, ‘A self-validating digital Coriolis mass-flow meter: an overview’, *Control Engineering Practice*, vol. 8, no. 5, pp. 487–506, 2000.

[4] J. Liu, T. Wang, Y. Yan, X. Wang, and L. Wang, ‘Investigations into the behaviours of Coriolis flowmeters under air-water two-phase flow conditions on an optimized experimental platform’, in *2018 IEEE International Instrumentation and Measurement Technology Conference (I2MTC)*, 2018, pp. 1551–1556.

[5] J. A. Weinstein, D. R. Kassoy, and M. J. Bell, ‘Experimental study of oscillatory motion of particles and bubbles with applications to Coriolis flow meters’, *Physics of Fluids*, vol. 20, no. 10, p. 103306, 2008.

[6] J. Hemp and J. Kutin, ‘Theory of errors in Coriolis flowmeter readings due to compressibility of the fluid being metered’, *Flow measurement and Instrumentation*, vol. 17, no. 6, pp. 359–369, 2006.

[7] N. T. Basse, ‘A review of the theory of Coriolis flowmeter measurement errors due to entrained particles’, *Flow Measurement and Instrumentation*, vol. 37, pp. 107–118, 2014.

[8] D. L. Gysling, ‘An aeroelastic model of Coriolis mass and density meters operating on aerated mixtures’, *Flow Measurement and Instrumentation*, vol. 18, no. 2, pp. 69–77, 2007.

[9] A. Rieder, W. Drahm, and H. Zhu, ‘Coriolis mass flowmeters: on measurement errors in two-phase conditions’, in *Proceeding of the 13th International Flow Measurement Conference*, Peebles Hydro, Scotland, UK, 2005.

[10] ‘Roxar MPFM 2600 MVG’. [Online]. Available: https://www.emerson.com/documents/automation/product-data-sheet-download-full-specs-roxar-en-us-170838.pdf. [Accessed: 26-Apr-2019].