Assessment of Coriolis meters as instrumentation for gas void fraction measurement in air–liquid multiphase flow in a pipeline riser system

Salem K Brini Ahmed
Faculty of Mining and Energy Engineering
Sebha University
Sebha, Libya
sal.brini@sebhau.edu.ly

Aliyu M. Aliyu
School of Engineering,
University of Lincoln
Brayford Pool, UK
AAliyu@lincoln.ac.uk

Yahaya D. Baba
Department of Chemical and Biological Engineering
University of Sheffield
Sheffield, UK
y.baba@sheffield.ac.uk

Rehil Omar Abdulhadi
Faculty of Mining and Energy Engineering
Sebha University
Sebha, Libya
reh.omar@sebhau.edu.ly

Hoi Yeung
Centre for Thermal Energy Systems and Materials
Cranfield University
MK43 0AL, Bedford, UK
h.yeung@cranfield.ac.uk

Abstract — *Measurement of void fraction in gas-liquid flow systems is important in determining pumping requirements, designing downstream facilities and in detecting off-design problems such as cavitation and flashing during operation. Hence, it is key that this parameter is known in real time during oil & gas production and other process operation. As a result, the use of clamp-on flow meters which operate on the Coriolis principle are useful for such purposes as they instantaneously measure the flow's density which can change depending on the gas fraction in the flowing mixture. In this study, we demonstrate the use of Coriolis mass flow meters in instantaneously measuring the void fraction in a multiphase mixture flowing in a 2-inch pipeline riser system at Cranfield University, UK. A Coriolis meter was installed on the vertical section of the facility. A set of experiments were conducted at fixed liquid superficial velocities of 0.25 and 1 m/s and air flow rates of 6-100 Sm^3/h (corresponding to 0.39–3 m/s). The instantaneous densities of the mixtures were recorded at 100 Hz acquisition frequency. These were then used to estimate the gas void fraction at the vertical section using the homogenous model for the mixture density. Also, a well-calibrated 16 by 16 wire mesh sensor (WMS) fitted at the same vertical location to validate the gas void fraction measurements of the Coriolis flow meter. It was found that the Coriolis flow meter presented excellent agreement with the WMS for void fraction measurement at high gas flow rates. We observed that the agreement coincided with conditions that exhibit core-peaking void fraction distributions, i.e., at conditions that are not bubbly flow. Hence, it may be concluded that the Coriolis flow meter can be used with some confidence in industrial application at these conditions.*

Keywords — Flow measurement, gas void fraction, two-phase flow, instrumentations, wire mesh sensor.

1 Introduction

Gas void fraction (GVF) determination is of paramount importance in multiphase pipeline design and operation. It has a direct bearing on the accurate determination of pressure losses, hence enabling the appropriate sizing of delivery pumps and loads on the pipeline. It also helps in designing downstream facilities such as surge tanks and slug catchers. Many research instrumentations used for GVF measurement such as capacitance and conductance tomography are rather complicated to use since they require long postprocessing steps and time to produce useable and actionable data. As such, their use in the field for detecting off-design problems such as cavitation, slugging, gas surges due to valve or seal leaks, and flashing during operation is limited. For this reason, instantaneous clamp-on GVF measuring devices such as Coriolis flow meters have proven very useful and are of immense importance. This is because they have been noted to have good accuracy for measuring mass flow and density, are very reliable and have low maintenance costs. Due to these advantages, they have been employed in various multiphase applications, many times incorrectly [1]. In numerous industrial applications involving liquids with low GVF, the gas phase manifests in the form of small bubbles. In such cases, bubbly flow is the dominant flow regime and is a challenge for Coriolis meters [2]. Reizner [3] noted that 90 to 95% of non-hardware Coriolis meter problems are due to entrained air bubble issues. Nevertheless, it has recently been used in many studies [4]–[7] to determine the gas void fraction from density measurements using the homogeneous model. This study therefore aims to assess the ranges of gas content that Coriolis meter GVF measurements give appreciably good results. We have done this by carrying out measurements with known inlet gas and liquid superficial velocities in a riser at Cranfield University and cross-validating with a capacitance wire mesh sensor (WMS) measurement.

2 EXPERIMENTAL SETUP AND PROCEDURE

2.1 Description of test rig

The experimental work in the present study were conducted in the 2-inch (52 mm internal diameter) riser system, which consists of a 10.5 m high vertical pipe linking to a 40 m long horizontal pipeline (shown in figure 1). The riser is a part of the test facility in the Flow Laboratory at Cranfield University's Oil and Gas Engineering Centre, United Kingdom. It is a computerised controlled test rig, which is able to supply, measure and control liquids and air flows to the test area. In this study, water can be supplied to the meter section by using a multistage Grundfos CR90-5 water pump. A remote-control system of Emerson DeltaV located in the control room is used to achieve the start-up, speed control and shutdown of this water pump. The air is also supplied by a compressor and stored in a large air receiver to reduce the pressure fluctuation from the compressor, before entering the riser system. The air from the receiver passes through filters and then entering a cooler to remove debris and condensates. Rosemount Mass flow meters designed for metering air flow rate from 0–120 Sm^3/h. are used for measuring the delivered air. Upon exit the measurement section, the air and water are separated. Air is released to the atmosphere, while the water is channeled to their respective coalescers where further separation occurs, and water is pumped for storage. The Emerson DeltaV automation system was used to control the flowrates of fluids and maintains steady state conditions during the operations. LabView system was also used to record pressure, temperature and injected gas flow data at a scan rate of 1000 Hz and recording rate of 100s. More details and description of the complete operating procedure of the three-phase test rigs are available in Yeung and Lao [8].

For the work carried out in this article, two main instruments were installed: A 16×16 wire mesh sensor WMS which is fitted in the vertical section near the riser top at 8.2 m from the base. Also, a Coriolis meter (Endress+Hauser, Promass 83F) was installed above the wire mesh sensor. Details of these instrumentation are given in the following section.

2.2 Instruments

Two main instruments have been used to carry out this study. They are, an Endress+Hauser Coriolis mass flowmeter, and a 16×16 capacitance wire mesh sensor (WMS).

2.1.1 Coriolis mass flowmeter

Principally, Coriolis flow meters are comprised of an oscillating measuring tube located inside and this tube oscillates constantly when a fluid flows through it. The measuring tube also has sensitive sensors at the inlet and outlet ends precisely record the consequent phase shift in the tube's oscillation geometry. The Coriolis effect causes the tube to oscillate in the opposite direction at the same time at the inlet and outlet ends of the tube. Accordingly, the highly previsioned sensitive sensors identify and registers these changes in the tube oscillations with reference to space and time. This phenomenon is described as phase shift, and this indicates the amount of liquid or gas flowing through the pipeline directly by this measurement principle.

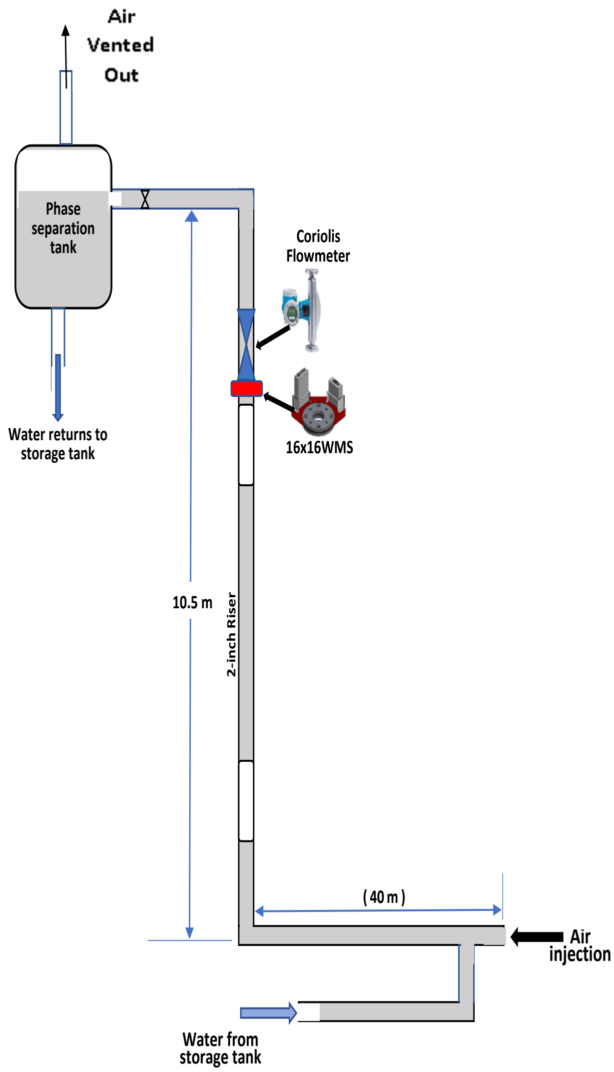


Fig. 1. Two-phase experimental riser flow rig.

Coriolis flowmeter also measures the density of a fluid mixture simultaneously as it measures the mass flow rate. Apart from the sensors recording the deflection of oscillation, it measures the oscillation frequency for density evaluation. When the tube is filled with less dense fluid it oscillates more frequently than when the tube is filled with denser fluid which is higher in density. Oscillating frequency is thus a straight way of measuring the fluid density.
Moreover, the temperature of the measuring tube is instantaneously estimated, and the signal corresponds to the fluids' temperature is also available as an output from the Coriolis flow meters. Therefore, the fluid density, temperature and mass flowrate are all measured simultaneously and independently.

In this study a type of Coriolis flow meter Endress and Hauser (E&H Promass 83F) is configured to the vertical riser system to give the fluid mass flow rate, fluid density and temperature simultaneously.

Figure 2 shows a Coriolis meter installed along the 2-inch vertical riser. This meter has a wide range of process conditions during measuring operations. In these experiments, the outputs of the Coriolis mass flowmeter were recorded through the LabView programme system.

Fig. 2. Coriolis mass flowmeter installed on the vertical section of the experimental rig.

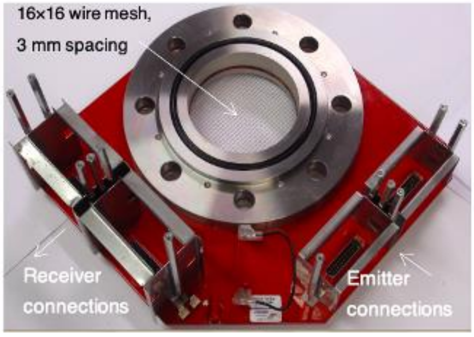
For the Coriolis flowmeter, the gas void fraction was estimated from the mixture density by using the homogenous model. The homogenous model [9]–[15] was used to calculate the void fraction for the Coriolis meter using the measured mixture density as follows:

$$\alpha_{Coriolis} = \frac{\rho_L - \rho_{mix}}{\rho_L - \rho_g} \quad (1)$$

Where ρ_L, ρ_{mix}, and ρ_g are the liquid, mixture, and gas densities respectively. The dispersed gas and the liquid phases are combined and modelled as a new continuous or "homogenous" phase. For this model to be used, the slip between the phases is usually taken to be small i.e., $u_l \approx u_g$ or the slip ratio $u_l/u_g \approx 1$.

2.1.2 Wire mesh sensor (WMS)

The 16×16 WMS is based on capacitance (permittivity) measurements of the fluids that manufactured by Helmholtz–Zentrum Dresden–Rossendorf (HZDR) [16] was employed for these gas/water flow measurements. Figures 2 a and b show the actual images for the 16×16 WMS with its capacitance electronic box and associated software.



(**a**)

(b)

Fig. 3. (a) installed capacitance WMS, (b) WMS electronic box (Model number: CAP 200).

It was utilised on the vertical section of the rig to obtain the signals for cross-sectional void fraction data. The WMS used consists of 16 receiver as well as 16 transmitter wires such that a measurement matrix is created for each time instant for which a set of realisations may be averaged. The wires are 250 µm in diameter that give a measuring matrix with 16×16 elements. The 16 wires made from stainless steel within each plane have a diameter of 0.12 mm and a wire spacing of 3.125 mm. The internal diameter of the two WMS, both with a 2.5 mm axial plane distance. These determine the instrument's spatial and temporal resolution. The WMS's measurement periphery can be considered rather pixelated but produces a diameter similar to the measurement section's pipe diameter. For actuating the transmitting electrodes, voltage pulses were provided in a progressive sequence. The receiver wire current originating when a delivered transmitter wire is triggered gives a measure of the capacitance of the flowing mixture in the adjoining control surface next to the intersecting point of the two wires. For capacitance, permittivity-based electronics give a corresponding linear relation between the relative permittivity (ϵ_r) and gas void fraction α . This relationship is known as the parallel model of mixture permittivity and is given as [17]:

$$\alpha_{WMS} = \frac{\epsilon_{r\ water} - \epsilon_{r\ mix}}{\epsilon_{r\ water} - \epsilon_{r\ air}} \quad (2)$$

where the subscript "mix" is short for "mixture" referring to the flowing gas/liquid mixture. Further important information about the capacitance wire mesh sensor may be obtained in more detail in Szalinski et al. [17] and Da Silva et al. [16].

2.2 Experimental procedure

In this study, the air-water experiments were performed by pumping the water at constant superficial velocity (water flow u_{sl}= 0.25 and 1.0 m/s) in the 52-mm riser and changing injected air flows through the horizontal flowline 40 m upstream of the riser base. Air volumetric flow rates ranging from 6 Sm^3/h (u_{sg} = 0.39 m/s) to 50 Sm^3/h u_{sg} = 3.0 m/s) were delivered to the measurements section in the vertical riser at each constant liquid (water) superficial velocity. Estimation for the superficial gas velocities u_{sg} were applied at the operating conditions of pressure and temperature at the measurement section where the instruments are installed. Before starting each set of experiments, the system is pressurised to 1 bar (gauge) using compressed air. For each flow condition, the facility was allowed about 25 minutes to stabilise before the measurements were taken. the system pressure and flowrates of the fluids in the facility were controlled by An Emerson DeltaV automation system. Also, a LabVIEW computer program system was used to record data from Coriolis flow meter (mass flow, mixture density and temperature) data at a scan rate of 1000 Hz and recording rate of 100 Hz for 3 minutes. In the WMS system, the CAP 200 electronic box and its associated software (shown in Figure 3 a & b) were used to obtain and pre-analyse the cross-sectional output signals.

In this work, a frequency of 1000 fps for a total time of 30 seconds was applied to collect data from the WMS. At each flow condition of the experiments, the void fraction GVF was measured using the outputs data from these instrumentations of the capacitance WMS and the Coriolis meter. The mean void fraction was obtained from the WMS measurements by averaging a set of time-resolved realisations for each node in the measurement grid.

3 Results and discussions

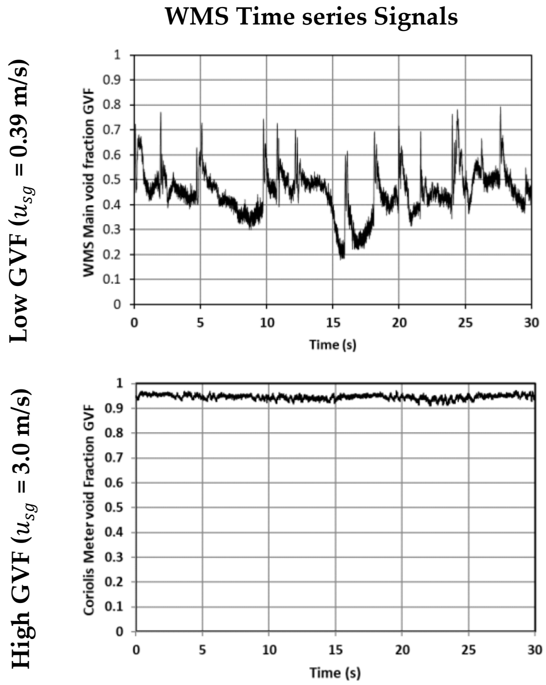
3.1 Time series of void fraction

Figure 4 shows the time histories of the void fraction calculated using the WMS and Coriolis meters respectively at u_{sg} of 0.39 m/s and 3.0 m/s. The presented time traces were all obtained at constant u_{sl} = 0.25 m/s. At lower gas injection of 0.39 m/s (air flow rate of 6 Sm^3/h) the void fraction time trace signals for both WMS and Coriolis flowmeter are fluctuating forming peaks and dips. However, more regular fluctuations are observed for wire mesh WMS void fraction data around an average value of 49% than in the Coriolis meter. Whereas at very high gas superficial velocity of about 3.0 m/s it shows approximately stable void fraction time traces for WMS data. It is also almost similar trend for Coriolis time series data time with very small fluctuations. This similarity of time series signals at higher gas flows is reflecting the agreement between wire mesh sensor and Coriolis flowmeter for average gas void fraction GVF measurements of 94% and 95% respectively.

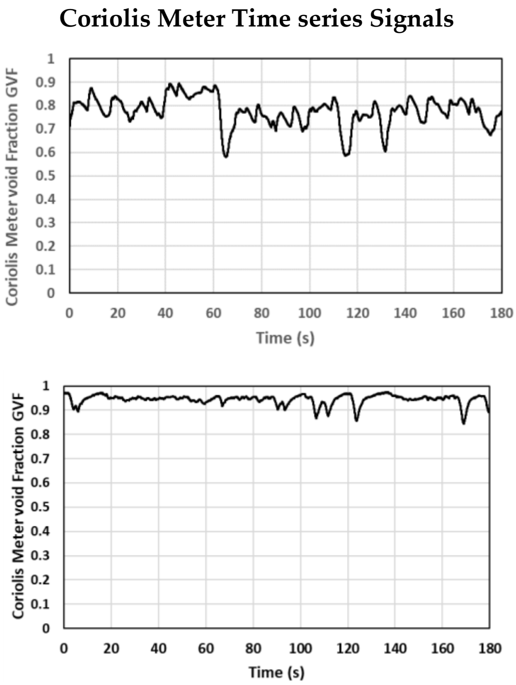
3.2 Void fraction distribution

In this study where air-water experiments were conducted in a riser, the void fraction value at each test point was collected at the top of the riser using the capacitance WMS and the Coriolis mass flow meter. For the WMS measurement, the mean void fraction was obtained directly by averaging the time series signals of the cross-sectionally averaged void fraction. In terms of the Coriolis mass flowmeter, the void fraction was determined by using the homogenous model to calculate the gas void fraction using the measured air-water mixture density (given in Equation 1). The mean of the signals presented in Figure 4 were calculated as arithmetic averages of all the sampled data given as follows:

$$\alpha_{mean} = \frac{1}{N}\sum_{t=1}^{N}\alpha_t \qquad (3)$$



(a)



(**b**)

Fig. 4. Comparison of time traces of **(a)** WMS and **(b)** Coriolis meter at $\boldsymbol{u_{sl}}$ = 0.25 m/s for $\boldsymbol{u_{sg}}$ = 0.39 m/s (top) and 3.0 m/s (bottom).

Where α_t is the GVF measured or calculated at time instant *t*. A comparison between the void fraction obtained by the WMS and Coriolis mass flowmeter plotted against each other is given in Figure 5. The cross-sectional distributions shown in the figure have previously been described in more detail by the authors [18]. From the plot in Figure 5 It can be observed that at high gas flow rates, the Coriolis flowmeter data exhibit excellent agreement with the WMS void fraction measurements. Whereas a slightly poor agreement and deviations between the void fraction data are appeared at lower gas flow conditions, and this is reflected in the plot. The wire mesh sensor's output data was able to provide appropriate descriptions for cross-sectional void distributions. These included phase fraction distribution along a central chord of the cross section and axial coloured sliced view images as shown in Figure 5 (red signifies the gas phase while blue indicates the liquid phase). Therefore, the agreement between the measured void fraction for the two meters at higher gas flowrates were found to coincide with a core-peaking void fraction profile, where a void fraction distribution higher in magnitude is presented around the centre of the pipe. This was also observed from the analysis reflected signals that obtained from the Wire mesh measurement, as demonstrated in figure 5. Conversely, at the lower gas flow conditions, the obtained data shows a wall-peaking void fraction profile (movement of gas bubbles towards the pipe wall). Thus, the void fraction distribution inside the vertical pipe noticeably reflects the meter's accuracy.

4 CONCLUSIONS

In this study an experimental investigation was carried out to assess void fraction measurements by a Coriolis mass flowmeter. The measurements were cross validated with those of a capacitance wire mesh sensor (WMS). This was done by carrying out the measurements with known inlet gas and liquid superficial velocities in a 2-inch vertical riser at Cranfield University. From the results, several conclusions may be drawn. It was found that excellent agreement exists between the WMS and Coriolis flowmeter void fractions at high gas flow rates where core-peaking void fraction profiles were observed at higher gas flow conditions. On the other hand, a slightly poor agreement at lower gas flow conditions was observed where the WMS presented wall-peaking void fraction distributions in the vertical riser at lower gas flow conditions. Due to these observations, we surmise that the gas flow distribution in the vertical riser impacts on the behaviour of the Coriolis flow meter. Nevertheless, it may be concluded that the Coriolis flow meter can be reliably used in industrial application at high gas flow conditions.

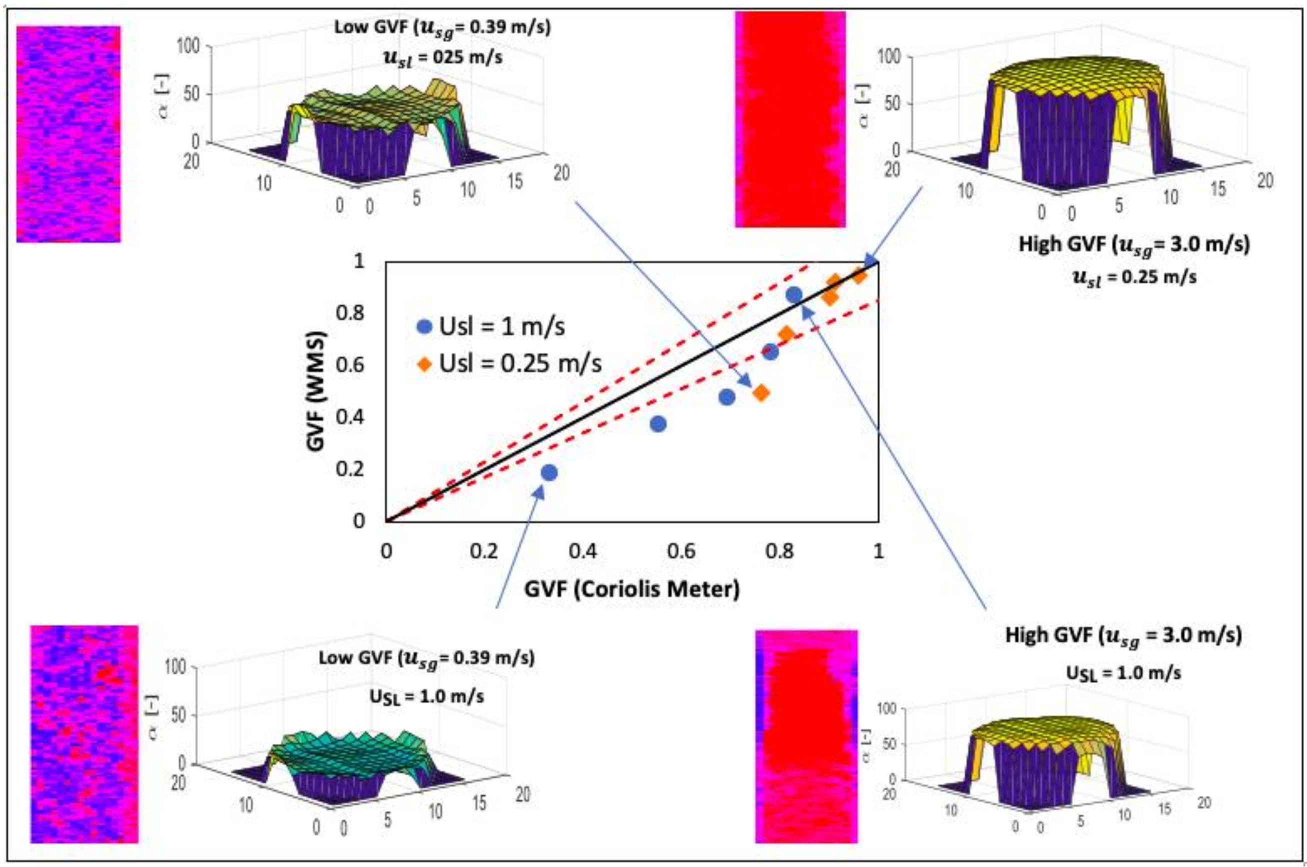


Fig. 5. The gas void fraction GVF measurements are plotted for a wide range of flow conditions of constant liquid superficial velocity of 0.25 and 1 m/s and variable gas superficial velocity between 0.39–3 m/s (6–50 Sm^3/hr) for each liquid superficial velocity.

REFERENCES

[1] Tim Patten, "Understanding the Challenges of Two-Phase Flow," Boulder, Colorado, USA, 2004. Accessed: Jan. 25, 2022. [Online]. Available: https://www.emerson.com/documents/automation/white-paper-understanding-challenges-of-two-phase-flow-micro-motion-en-66308.pdf

[2] H. Zhu *et al.*, "From disturbance to measurement: Application of Coriolis meter for two-phase flow with gas bubbles," *Flow Measurement and Instrumentation*, vol. 79, p. 101892, Jun. 2021, doi: 10.1016/J.FLOWMEASINST.2021.101892.

[3] J. Reizner, "Coriolis - the almost perfect flowmeter," *Computing and Control Engineering*, vol. 14, no. 4, pp. 28–33, Aug. 2003, doi: 10.1049/cce:20030407.

[4] M. Ferrando, M. Caminale, F. Reggio, and P. Silvestri, "Design and Testing of a Static Rig for Tesla Turbine Flow Visualization," Jun. 2021. doi: 10.1115/GT2021-59175.

[5] F. Zhang, F. Dong, and C. Tan, "High GVF and low pressure gas–liquid two-phase flow measurement based on dual-cone flowmeter," *Flow Measurement and Instrumentation*, vol. 21, no. 3, pp. 410–417, Sep. 2010, doi: 10.1016/j.flowmeasinst.2010.06.004.

[6] M. Henry, M. Tombs, M. Zamora, and F. Zhou, "Coriolis mass flow metering for three-phase flow: A case study," *Flow Measurement and Instrumentation*, vol. 30, pp. 112–122, Apr. 2013, doi: 10.1016/j.flowmeasinst.2013.01.003.

[7] Q. Hou, K. Xu, M. Fang, Y. Shi, B. Tao, and R. Jiang, "Gas–Liquid Two-Phase Flow Correction Method for Digital CMF," *IEEE Transactions on Instrumentation and Measurement*, vol. 63, no. 10, pp. 2396–2404, 2014, doi: 10.1109/TIM.2014.2310031.

[8] Hoi Yeung and Liyun Lao, "Cranfield University Three-Phase Test Facility Operating Manual," Cranfield, UK, 2013.

[9] A. M. Aliyu, L. Lao, and H. Yeung, "A New Empirical Correlation for Entrained Droplet Fraction Prediction in Co- current Gas – Liquid Annular Two-phase Flow in Large Diameter Pipes 1 Introduction," *APCChE 2015 Congress incorporating Chemeca 2015*, no. 3131582, pp. 90–101, 2015.

[10] A. A. Almabrok, A. M. Aliyu, L. Lao, and H. Yeung, "Gas/liquid flow behaviours in a downward section of large diameter vertical serpentine pipes," *International Journal of Multiphase Flow*, vol. 78,

pp. 25–43, 2016, doi: http://dx.doi.org/10.1016/j.ijmultiphaseflow.2015.09.012.

[11] A. M. Aliyu, L. Lao, H. Yeung, and A. A. Almabrok, "A Comparative Analysis of Interfacial Friction Factor Correlations for Adiabatic Co - Current Gas – Liquid Annular Two - Phase Flow in Large Diameter Pipes," Proceedings of the World Congress on Mechanical, Chemical, and Material Engineering (MCM 2015), no. 280, pp. 280-1–9, 2015, [Online]. Available: http://avestia.com/MCM2015_Proceedings/files/papers/HTFF280.pdf

[12] J. X. F. Ribeiro, R. Liao, A. M. Aliyu, and Z. Liu, "Upward interfacial friction factor in gas and high-viscosity liquid flows in vertical pipes," *Chemical Engineering Communications*, vol. 207, no. 9, pp. 1234–1263, 2020, doi: 10.1080/00986445.2019.1647180.

[13] A. A. Almabrok, A. M. Aliyu, Y. D. Baba, L. Lao, and H. Yeung, "Void fraction development in gas-liquid flow after a U-bend in a vertically upwards serpentine-configuration large-diameter pipe," *Heat and Mass Transfer/Waerme- und Stoffuebertragung*, vol. 54, no. 1, pp. 209–226, 2018, doi: 10.1007/s00231-017-2118-0.

[14] M. A. Woldesemayat and A. J. Ghajar, "Comparison of void fraction correlations for different flow patterns in horizontal and upward inclined pipes," *International Journal of Multiphase Flow*, vol. 33, no. 4, pp. 347–370, 2007, doi: 10.1016/j.ijmultiphaseflow.2006.09.004.

[15] M. J. da Silva, S. Thiele, L. Abdulkareem, B. J. Azzopardi, and U. Hampel, "High-resolution gas–oil two-phase flow visualization with a capacitance wire-mesh sensor," *Flow Measurement and Instrumentation*, vol. 21, no. 3, pp. 191–197, Sep. 2010, doi: 10.1016/j.flowmeasinst.2009.12.003.

[16] L. Szalinski *et al.*, "Comparative study of gas–oil and gas–water two-phase flow in a vertical pipe," *Chemical Engineering Science*, vol. 65, no. 12, pp. 3836–3848, Jun. 2010, doi: 10.1016/j.ces.2010.03.024.

[17] S. K. Brini Ahmed, A. M. Aliyu, A. Ehinmowo, and H. Yeung, "Effect of Riser Base and Flowline Gas Injection on the Characteristics of Gas-Liquid Two-Phase Flow in a Vertical Riser System," Aug. 2020. doi: 10.2118/203677-MS.