

Advancing two-phase wet gas flow measurement with Coriolis meters: optimal sensor orientation and a new model development

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ABSTRACT

In this study, a novel wet gas model was developed based on the internal parameter of a Coriolis prototype to measure two-phase wet gas flow. Additionally, an optimal orientation of the Coriolis sensor was proposed to address challenges in the horizontal wet gas flow. Two Coriolis prototypes— one with a long-bent flow tubes (Type A), and another with short-bent flow tubes (Type B) – were employed to conduct tests in both vertical upward and horizontal pipelines. Different sensor axial angles (0, 40, 90, and 180 degrees) were selected for testing in the horizontal section. Among different orientations (angles), it was found that the 40-degree angle outperforms the other installations in terms of the response proximity and over-reading of gas flow (OR). To understanding the impact of flow pattern on the response, a detailed analysis of different flow patterns in the wet gas was considered. A new correlation was developed between the damping factor of the Coriolis and both X_{LM} and the total mass flow rate, leading to the proposal of a new wet gas model to predict gas and liquid flow rates with acceptable accuracy. In scenarios involving higher Froude numbers and annular flow patterns, which are more likely to occur, the Mean Absolute Percentage Error (MAPE) for the entire range of wetness ($0 < X_{LM} < 0.3$) is 3.9 % for gas flow rate and 4.3 % for liquid flow rate with an uncertainty of 2.7 %.

Keywords: Coriolis, Damping factor, Flow pattern, Sensor orientation, Wet gas model

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Nomenclature

English Symbols

A	The cross-sectional area of the pipe (m ²)	V_{out}	The output voltage of conductance ring in a wet gas flow (V)
D	Pipe diameter (m)	UR	Under-Reading of meter in the wet gas flow (-)
Df	Damping factor (A/m)	U	Flow velocity (m/s)
DfR	Reduced damping factor (-)	w	Weight coefficients in Eq. (19)
Fr_g	Gas Froude number (-)	X_{LM}	Lockhart-Martinelli parameter (-)
Fr_l	Liquid Froude number (-)		
GVF	Gas Volumetric Fraction (-)		
I	Exciter current (A)		
L	Coriolis tube length		
$\dot{m}_l$	Liquid mass flow rate (kg/hr)		
$\dot{m}_g$	Gas mass flow rate (kg/hr)		
MAPE	Mean absolute percentage error (%)		
NV	Normalized voltage of conductance ring (-)		
OR	Over-Reading of a meter in the wet gas flow (-)		
OA	Oscillation amplitude (m)		
PE	Percentage error (%)		
r	Coriolis tube radius		
V_{min}	The output voltage of conductance ring when just air is in the pipe (V)		
V_{max}	The output voltage of conductance ring when just water is in the pipe (V)		

Greek Symbols

α	Aspect ratio
ρ	Density (kg/m ³)

Subscripts

g	gas
l	liquid
total	Total flow rate
Ref.	Reference flow rate
sg	Superficial gas
sl	Superficial liquid
unc.	Uncorrected flow rate

1. Introduction

Wet gas refers to a gas flow containing a minor quantity of liquid. It is prevalent in various industrial processes, including natural gas extraction and steam production. A gas-liquid mixture with a gas volumetric fraction (GVF) exceeding 95% can be classified as wet gas [1]. More generally, wet gas flow is defined as any gas-liquid flow characterized by a condition where $X_{LM} < 0.3$ [2].

Widely adopted wet gas meters generally integrate multiple single-phase meters to improve measurement accuracy [3]. Among these hybrid meters, the use of a void fraction measurement device to estimate wetness is more common [2]. Although this approach enhances measurement reliability, it comes at the cost of increased complexity and higher expenses. In industrial applications, utilizing a single meter capable of delivering comparable or superior performance without increasing complexity or cost is highly desirable. Coriolis meters (CMs) have significant potential to fulfil these necessities if their performance in wet gas can be thoroughly analysed.

Generally, CMs have good accuracy in the measurement of pure liquid and gas flow [4]. However, significant measurement errors and repeatability issues have been reported specifically in wet gas conditions [5–7]. Nevertheless, over the past decade, advancements in digital machinery have led to significant evolution in Coriolis technology, particularly drive signals [8]. Additionally, with a better understanding of two-phase flow behaviour,

improvements have been made to the design of Coriolis sensors. Improvements in sensor design include modal separation, establishing a balance in the tubes movement and shielding the device from external vibrations [9]. Earlier Coriolis metering transmitters faced challenges in sustaining the oscillation of the flow tube under highly damped conditions resulting from the liquid and gas mixture [8]. However, ensuring optimal oscillation alone does not assure the accuracy of Coriolis meters in wet gas flow, and significant errors in mass flow rate and density have been documented under such conditions [10–12]. To address these errors and establish a model, it is preferable to utilize parameters that are obtained within the meter itself.

Several physical models have been developed to correct these errors but limited to entrained gas and bubbly or stratified flow and GVF less than 50 % [13–18]. Despite those developments, questions remain about the applicability of those models to flow conditions with a high GVF or wet gas flow.

Literature review showed that the studies of Coriolis flow meters in wet gas flow have received comparatively less attention. Lansangan et al. [19] were among the earliest studies that attempted to assess wetness using Coriolis data in a wet gas flow. Two approaches were considered: 1) utilizing methods that apply for low-range GVF to correlate experimental density and mass flow in wet gas, and 2) assessment the wetness by a differential pressure model such as Chisholm. They appeared to be more interested in the second approach; however, no comparison was made between the two approaches. Geng et al. [20] performed comparative studies on two identical Coriolis meters, one positioned vertically and the other horizontally, both subjecting to the same gas and liquid flow rates. It was found that the horizontal orientation returned a better output signal in terms of data scattering compared to the vertical type. The details of their work will be discussed later. A significant enhancement in the performance of Coriolis meters was achieved by utilizing drive gain to detect the presence of liquid within the meter and then attempting to compensate for liquid in wet gas [9]. However, this parameter wasn't applied to evaluate the wetness or liquid flow rate.

Some research was conducted based on splitting procedure which separates liquid content from a wet gas flow before being metered. Although the installation and maintenance are costly, this approach is extensively utilized across wet gas industries [21]. For example, a system which uses three Coriolis meters in series to measure the wet gas flow was suggested by Dayev and Yuluyev [22]. The system operation is based on a separation procedure with a liquid content limit of less than 5 %. However, employing three Coriolis devices alongside a separation system may not be considered practical under industrial conditions. A Coriolis device integrated with an internal separation mechanism was proposed by Meribout et al. [23]. Their experimental tests covered not only wet gas flow but also a wide range of GVF. They employed the bubble model and drive gain in conjunction with a neural network to devise a correction algorithm. Nevertheless, a homogenous model to establish the GVF was assumed, and no further approach was presented to determine the liquid flow rate from the drive gain.

Considering the preceding analysis, a substantial gap exists in the development of the Coriolis device in the wet gas conditions, outlined as follows:

- No consideration has been given to tube geometry and its influence on the Coriolis response in wet gas flow.
- Sensor orientation (angles) have been largely overlooked.
- The effect of flow patterns on the Coriolis response under these conditions have been disregarded.
- Lack of a correction model which can measure the liquid and gas flow rate at the same time.

Given this, an experimental investigation was conducted to assess the performance of different Coriolis prototypes (Type A and B) under wet gas conditions. Exploration of the influence of different configurations (vertical and horizontal) on the response of each Coriolis

prototype was also carried out. As a further step, the effects of different sensor angles of Coriolis in a horizontal wet gas flow were investigated. Notably, the article will discuss the impact of various flow patterns on the response of Coriolis prototypes, an aspect often overlooked in prior research. Finally, a novel model has been developed to measure gas and liquid flow rates in wet gas simultaneously, utilizing the damping factor as an internal parameter of the Coriolis prototype. This model integrates damping factor data, dry gas Over-Reading (OR), and the Under-Reading of total mass (UR) obtained from the Coriolis.

The findings are structured as follows: In Section 2, the experimental devices and methods employed in the tests are discussed. Section 3 begins by analysing the Coriolis response in wet gas flow. Various topics are covered, including the output rate (OR) of each Coriolis prototype, the effects of different installation positions (horizontal versus vertical), and various orientations of sensor within the horizontal position (angles). Furthermore, the section explores the influence of flow patterns on the response. Subsequently, an analysis of the response of short-bent tube Coriolis (Type A) to establish a wet gas model is presented. Finally, a novel correction algorithm for the Coriolis is introduced, and the associated error results are outlined. Additionally, the robustness of the model is discussed using previously available data in Section 3. In Section 4, the conclusion is presented.

2. Experimental apparatus and method

2.1. Method

Coriolis devices typically include an excitor coil, along with two pickoff sensors at the inlet and outlet, a transmitter and one or more mechanical flow tubes. When fluid begins to flow through the measuring tubes, the fluid's movements cause additional twisting on their oscillation. During operation the excitor coil causing tubes to move in opposite directions at their natural resonant frequency. The output voltage generated by the two pickoff sensors forms a sine wave. These sensors detect changes in the oscillation of the tubes over time and space as the "phase difference" or "phase shift" which can be further processed to determine the mass flow. Additionally, the change in frequency of vibration due to the mass of the flowing fluid is directly related to the density of the fluid. The Coriolis transmitter monitors and controls the oscillation of the flow tubes, extracts sensor signals, and calculates density and flow. It also registers the temperature of the measuring tube to compensate for thermal effects.

To investigate the effect of different type of Coriolis meters, two Coriolis prototypes with different bent-tube were selected and their results were compared: short-bent (Type A), and long-bent (Type B) as depicted in [Fig. 1](#). Both Coriolis prototypes consist of a dual bent tube installed in a process pipe with an internal diameter of 50 mm.

Another important definition for Coriolis flow meters is the "Aspect Ratio", which can be defined as follows:

$$\alpha = \frac{L}{r} \quad (1)$$

where α is the aspect ratio, L Coriolis tube length, and r inner Coriolis tube radius. With this value in mind, it becomes possible to quantify the Coriolis devices with higher expectations of favourable results in wet gas conditions. [Table 1](#) presents the differences in bent tube length of each Coriolis prototype.

Table 1 The differences in bent tube length, inner radius and aspect ratio of each Coriolis prototype.

Coriolis type	L (mm)	r (mm)	α (—)
Type A	460	13	35.4
Type B	760	14	54.3

2.2. Experimental apparatus

The experimental tests were conducted at the Process Systems Engineering (PSE) Laboratory at Cranfield University. The schematic of the facilities is depicted in Fig.2, and further details can be found in [24]. Air and water were chosen as the working fluids for the experiments. A distance of 10D is generally sufficient to mitigate flow disturbances. However, to enhance accuracy, a much greater distance, exceeding 30D, was considered both upstream and downstream of each meter in the horizontal position. For the vertical position, a minimum distance of 100D from the bend was maintained.

Various auxiliary sensors, such as pressure and temperature sensors, are available in the flow loop to compare and validate the internal temperature and pressure data measured by the Coriolis prototypes. Additionally, the actual void fraction was determined using a ring electrode sensor. Moreover, the signal waveform of the conductance sensor was utilized to derive the probability density function, serving as a method to validate the flow pattern. A high-speed camera (i-SPEED) capable of recording up to 2000 frames per second (fps), with resolution 1280× 1024 and 16 GB memory, a pixel size of 21 micron, and with ISO setting of 4800 in monochrome and 1600 in colour, was used to capture the instantaneous flow pattern in the horizontal section. To focus on and clearly observe the flow motion inside the pipe, the i-Focus feature was utilized, allowing more accurate tracking of the droplets. Table 2 lists the specifications of the test facility and their accuracy. Based on the Froude number, the observed flow pattern map and wet gas test matrix are shown in Fig. 3, corresponding to a superficial gas velocity range of 6.9 to 27.4 m/s and a superficial liquid velocity range of 0.01 to 0.39 m/s. Fr_g and Fr_l can be defined as:

$$Fr_g = \frac{U_{sg}}{\sqrt{gD}} \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} = \frac{\dot{m}_g}{A\sqrt{gD}} \sqrt{\frac{1}{\rho_g(\rho_l - \rho_g)}} \quad (2)$$

$$Fr_l = \frac{U_{sl}}{\sqrt{gD}} \sqrt{\frac{\rho_g}{\rho_l - \rho_g}} = \frac{\dot{m}_l}{A\sqrt{gD}} \sqrt{\frac{1}{\rho_l(\rho_l - \rho_g)}} \quad (3)$$

where U_{sg} and U_{sl} respectively represent superficial gas and liquid velocity, ρ_g and ρ_l respectively represent gas and liquid density, $\dot{m}_g$ and $\dot{m}_l$ respectively represent gas and liquid mass flow rate, A is the cross-sectional area, D is the pipe diameter and g is the gravitational acceleration.

Two Memograph devices (RSG45), advanced data manager, were employed to record the Coriolis outputs at a sampling frequency of 1 Hz and line pressure ranging from 0.1 to 0.4 MPa.

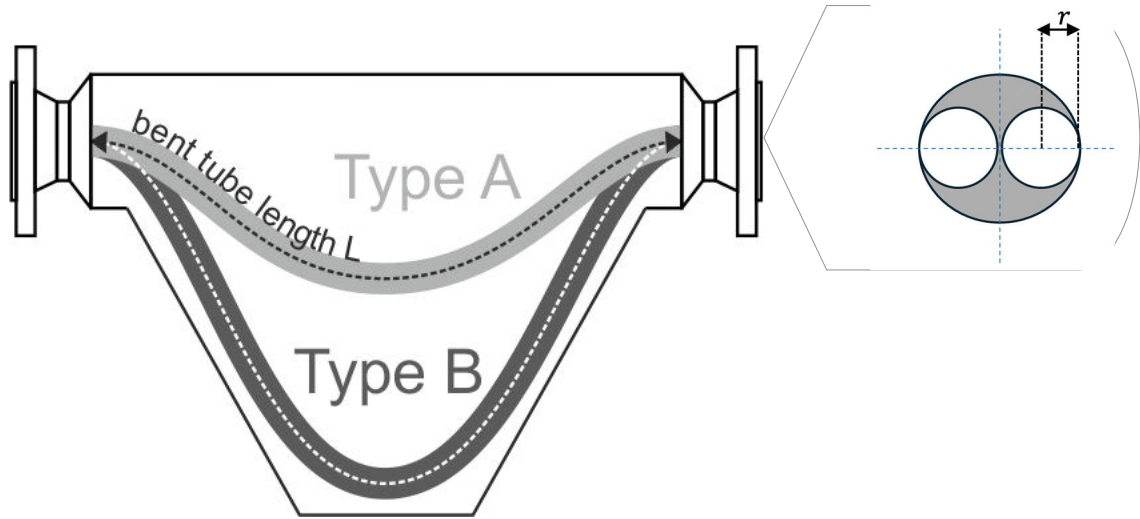


Fig. 1. Coriolis prototypes applied to this study: Short-bent (Type A) and Long-bent tube (Type B).

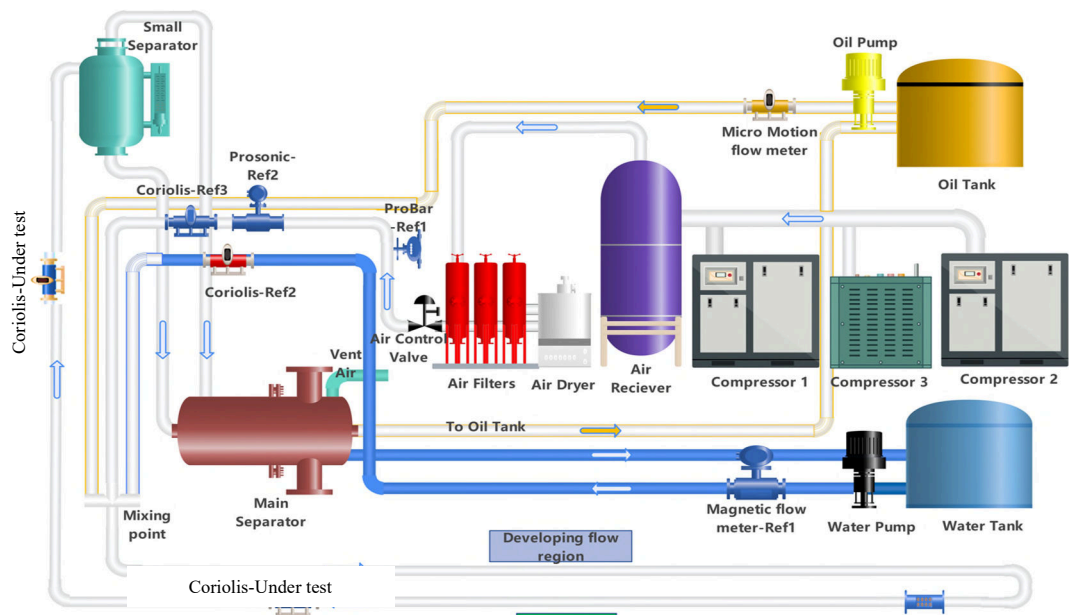


Fig. 2. Diagram of wet gas facilities and flow loop.

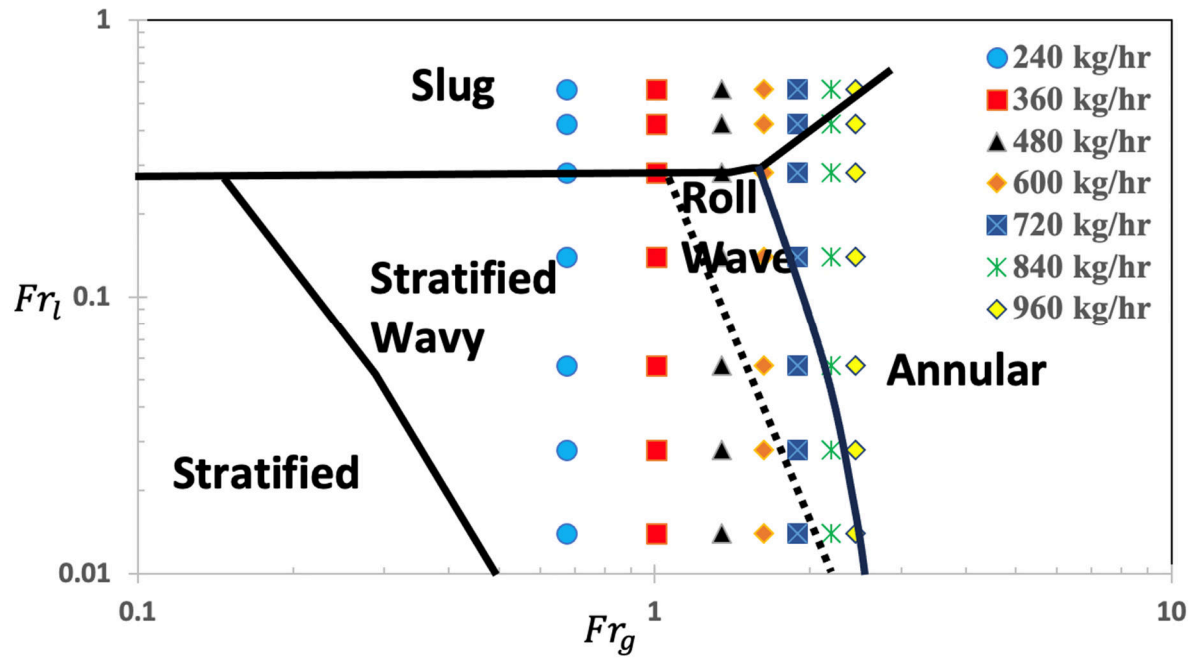


Fig. 3. Flow pattern map and wet gas test matrix in the horizontal pipe with a line pressure 0.4 MPa.

Table 2

Major specifications of reference devices employed in the experiment.

Parameters	Range	Accuracy (of Full Scale)
Pressure	100– 400 kPa	$\pm 0.25 \%$
Temperature	18 – 22 °C	$\pm 0.1 \%$
Liquid mass flow rate (Rosemount 8742c)	0 – 1.0 kg/s	$\pm 0.1 \%$
Gas mass flow rate (PROMASS F 300)	240 – 960 kg/hr	$\pm 0.25 \%$
Gas mass flow rate (Prosonic G300)	240 – 960 kg/hr	$\pm 0.5 \%$
Conductance Ring	–	$\pm 5 \%$

3. Results and Discussions

The study initially examined the influence of various configurations and sensor orientations on the response of each Coriolis prototype. Subsequently, efforts were made to explore the impact of flow patterns as far as possible. These parameters are crucial for developing an effective correction model for Coriolis meters in wet gas flow, and they have not been previously studied.

According to the results and by applying a damping factor as an internal parameter of the Coriolis, a new correction model was established to calculate gas and liquid flow rates.

3.1. Overall analysis of Coriolis prototype performance

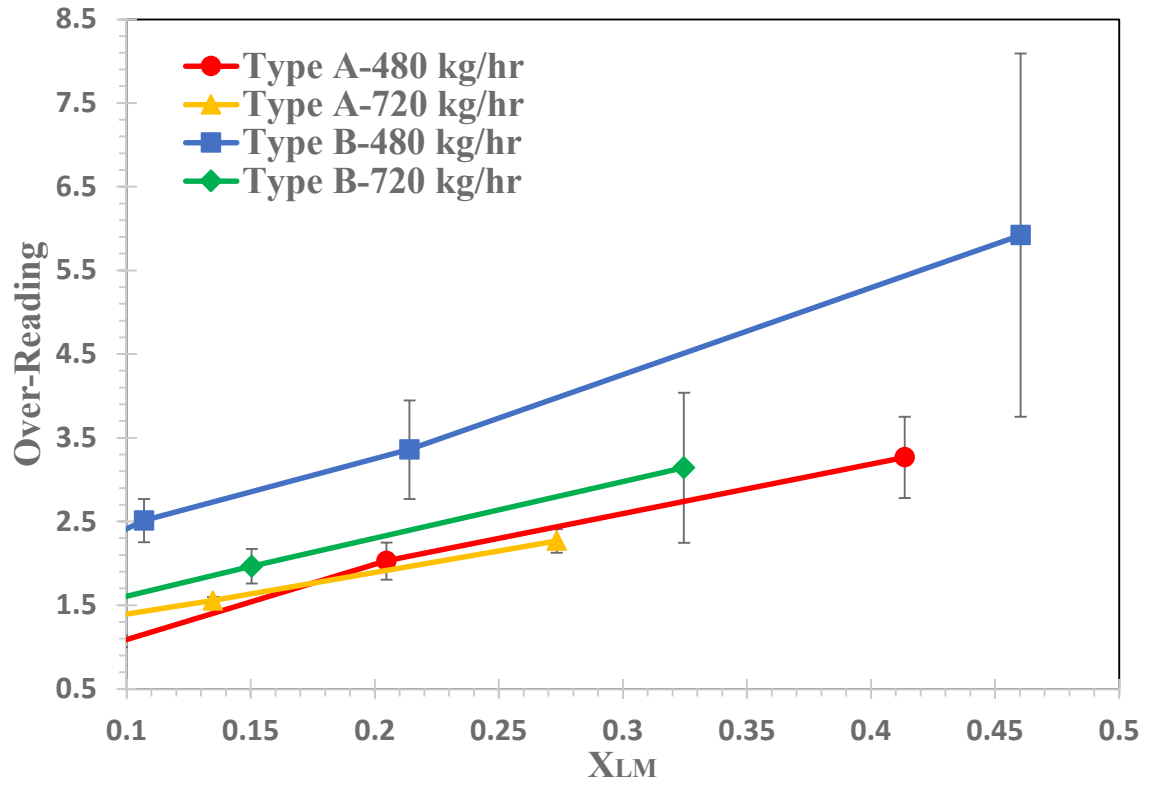
The over-reading (OR) of Coriolis prototypes for the gas flow in the classic horizontal position, with the sensors in the downward position, are depicted in Fig. 4 at high (Fig. 4a) and low X_{LM} (Fig. 4b). The gas OR and Lockhart-Martinelli parameter (X_{LM}) is defined as:

$$OR = \frac{\dot{m}_{g,unc.}}{\dot{m}_{g,Ref.}} \quad (4)$$

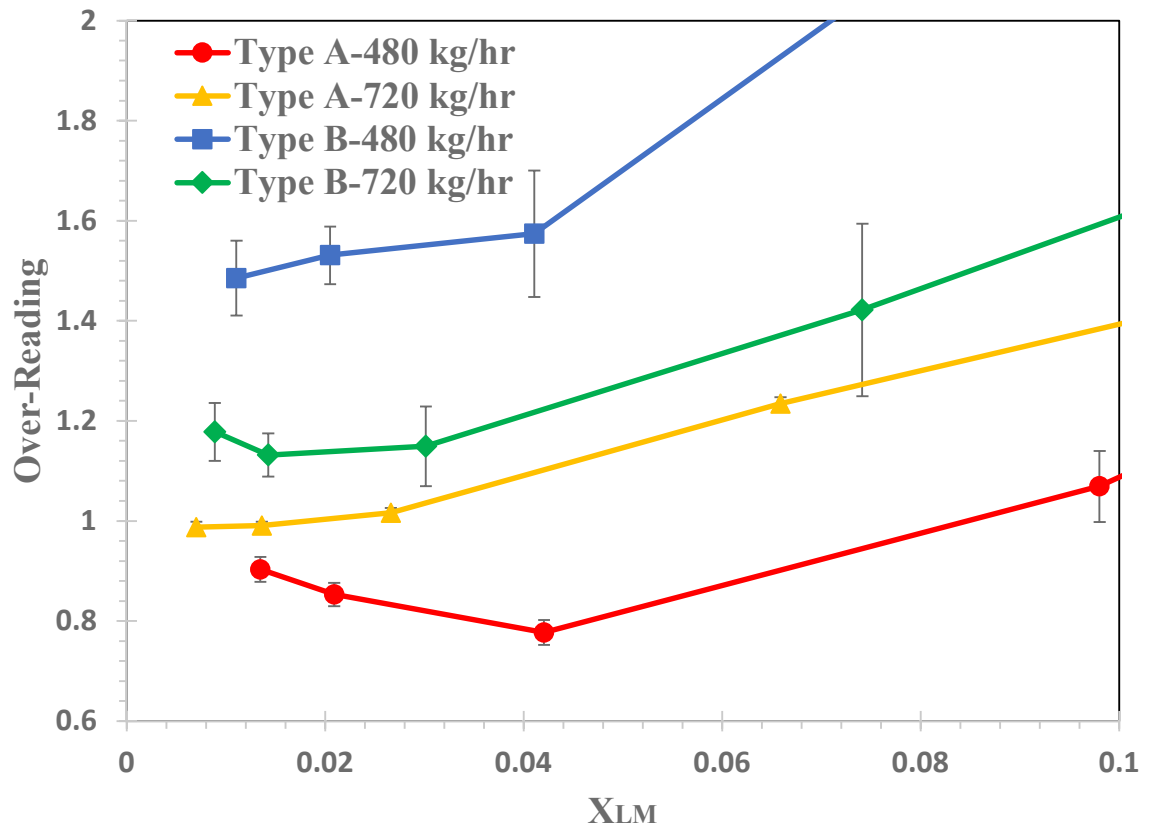
$$X_{LM} = \frac{\dot{m}_{l,Ref.}}{\dot{m}_{g,Ref.}} \cdot \sqrt{\frac{\rho_g}{\rho_l}} \quad (5)$$

where $\dot{m}_{g,unc.}$ and, $\dot{m}_{g,Ref.}$ represent the uncorrected mass flow rate measured by the Coriolis prototypes and the gas mass flow rate from the reference meter both in $\text{kg} \cdot \text{hr}^{-1}$, respectively. ρ_g and ρ_l demonstrate gas and liquid density, respectively, which are calculated using temperature and pressure data within the line.

The results in Fig. 4 indicate that increasing X_{LM} generally results in higher OR for both Coriolis prototypes, with Coriolis Type B showing higher OR. Furthermore, higher wetness (presented as X_{LM}) causes more deviations and data scattering in the Coriolis response, which will be elaborated later. Standard deviations were used as error bars to demonstrate these fluctuations in the response. Decreasing X_{LM} reduces both OR and the scattering in the data points for either Coriolis prototype. For Coriolis Type A, distinct data points converge into a single point at very low X_{LM} because of low data scattering. On the contrary, data scattering is obvious for Coriolis Type B even at low liquid flow rates. In the comparison of different Coriolis prototypes in the wet gas flow, it can be concluded that the Coriolis Type A with shorter bent tube exhibits better results in terms of OR and data scattering in the whole range of X_{LM} . The impact of gas flow rate on the Coriolis response will be studied in the subsequent discussion.



(a) High X_{LM}



(b) Low X_{LM}

Fig. 4. Comparison of OR of different Coriolis prototypes installed in the horizontal position at high (a) and low X_{LM} (b) and line pressure 0.4 MPa.

3.2. Effects of horizontal and vertical installations of the meters

Given the critical nature of different installation and its impact on the Coriolis response, comprehensive tests were conducted to find out the details, which have been almost ignored in the literature. In the context of wet gas flow, only reference [20] presented some findings for both vertical and horizontal configurations. Their observations indicated better results when installing the Coriolis device horizontally compared to the vertical orientation. According to their data, the vertical position exhibited significant data scattering and even negative readings. Unfortunately, specific details about the type of Coriolis device were not provided. However, by considering gas flow rates of less than 600 kg/hr and a high liquid flow rate (0.11-1.5 kg/s), it can be supposed that the Coriolis device in the vertical flow likely predominantly sensed a churn flow pattern [2], rather than an annular one. It potentially influenced the obtained results.

To investigate this further, Coriolis Type A and B were installed vertically, and experiments were conducted under identical conditions as those in the horizontal position. The comparison at various flow rates for Coriolis Type A and B are depicted in Fig. 5 & 6, respectively. The output for the Coriolis Type A presents a fair overlap between vertical and horizontal data, except for deviations observed in the horizontal installation of Coriolis Type A at low X_{LM} and 480 kg/hr gas flow rate. Remarkably, the outcomes at higher gas flow rates (720 kg/hr) almost coincide, suggesting a common annular flow pattern for both configurations. However, there is an obvious difference in data scattering for vertical and horizontal positions. The vertical position presents lower data scattering at higher X_{LM} and the same gas and liquid flow rates. The same or at least similar results were expected for the Coriolis Type B. Nevertheless, more deviations were observed in the results between the vertical and horizontal orientations for Coriolis Type B (Fig. 6). For Coriolis Type B, in both configurations, lower gas flow rates resulted in the same OR, whereas at the higher gas flow rate, a divergence was apparent for the OR response. In other words, at high gas flow and under the same annular flow pattern for both configurations, the OR in the vertical position was higher than the horizontal one contrary to the expected outcome.

The initial question arises regarding the notable difference in OR data at the vertical position for Coriolis Type B compared to Coriolis Type A. The key distinction comes from the aspect ratio and longer tube length of Coriolis Type B. This difference could be interpreted as potentially involving the effect of gravity and changing the flow pattern in the vertical position. Mounting a long tube in the vertical configuration sets the inlet and outlet of the tubes almost straight with a slight angle after the inlet and before the outlet. These relatively long zones differ from the middle part of the Coriolis and might cause droplets and the liquid film to descend and settle at the bottom of the tube due to gravitational force. In the middle of the bent tube, this liquid starts to ascend through the vertical part, forming a liquid film in this section. As a result, three distinct regions can be identified for the Coriolis Type B in the vertical position, each possibly exhibiting different flow patterns. These patterns may not align with churn or annular flow patterns, especially at lower gas flow rates. However, with an increase in gas flow rate and the generation of sufficient dragging force, all the liquids in the tube can be carried as an annular or mist annular flow. This explanation may clarify the proximity of the results for lower gas flow rates in the vertical Coriolis Type B to the horizontal response.

However, both Coriolis meters present a better closeness of OR response at different gas flow rates in the vertical configuration. Additionally, vertical position shows less standard deviation compared to the classic horizontal position or 0-degree (belly down). Nevertheless, further assessments are required to determine the optimal configuration, which will be addressed in the subsequent sections.

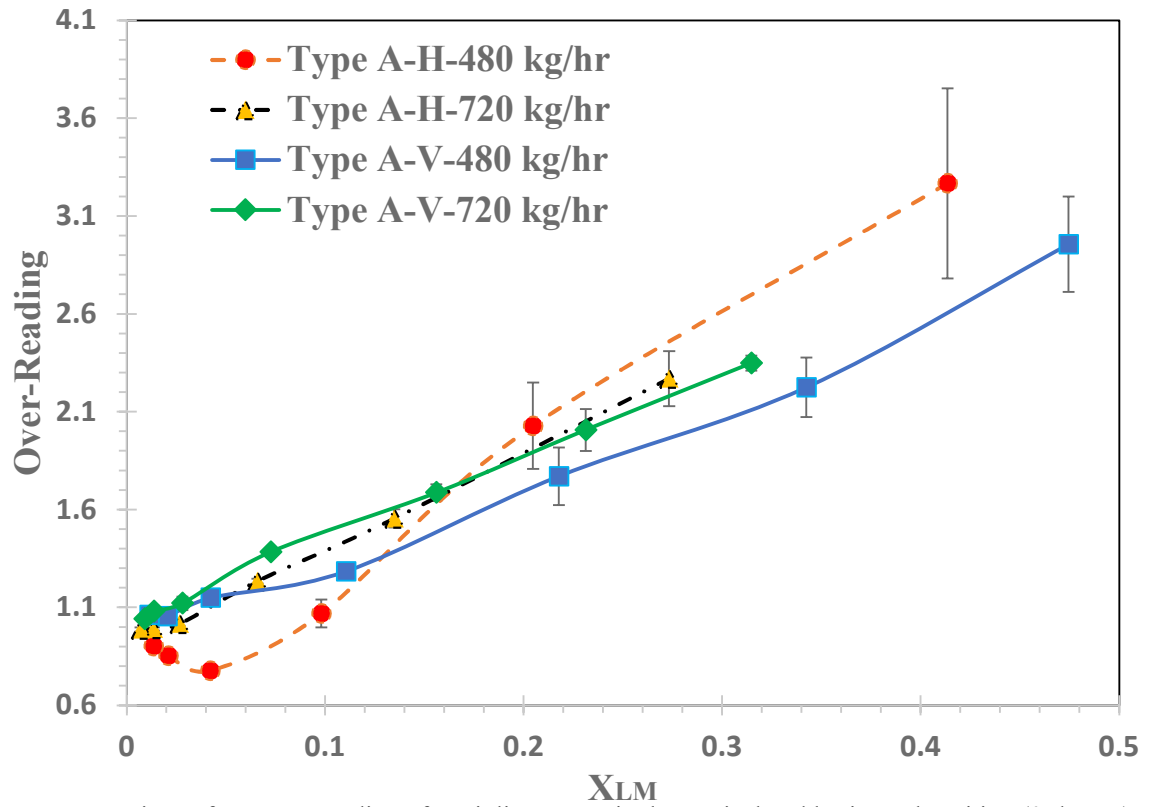


Fig. 5. Comparison of gas over-reading of Coriolis Type A in the vertical and horizontal position (0-degree) and line pressure 0.4 MPa.

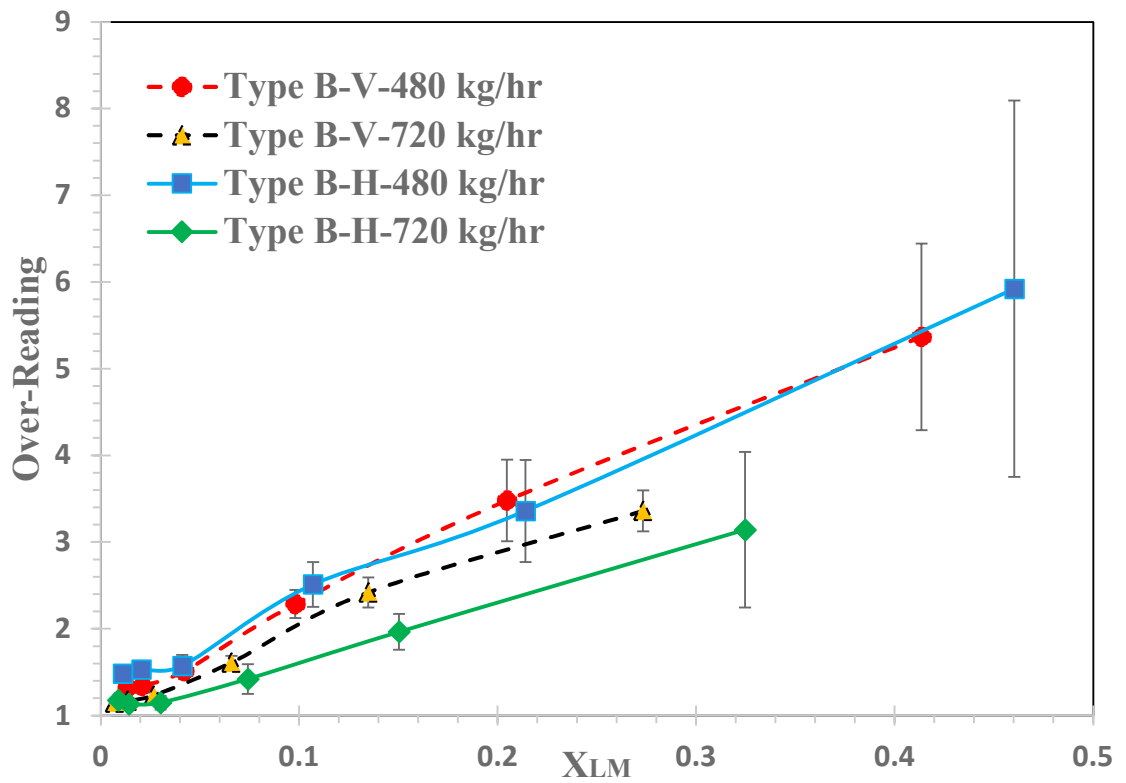


Fig. 6. Comparison of gas over-reading of Coriolis Type B in the vertical and horizontal position and line pressure 0.4 MPa.

3.3. Effect of different sensor tube angles on the response

A critical aspect for Coriolis is the orientation or angles of the sensor when they must be installed horizontally. For pure liquid flow, it is generally recommended to install the tubes in a downward position to minimize the potential impact of gas bubbles [25]. For pure gas flow, either an upward vertical flow or tubes upward in a horizontal position has been suggested [26]. Nevertheless, there are no known experimental tests that have identified the optimal orientation of sensor in a horizontal wet gas flow. To address this, a series of experiments was conducted for both Coriolis Type A and B at various tube angles: 0-degree; 40-degree; 90-degree, and 180-degree as shown in Fig. 7 (a). These angles were measured using an industrial protractor (Starrett 180° Bevel protractor) and were checked with a digital one.

The results for Coriolis Type A are presented in Fig. 8. Due to space constraints, a 90-degree angle was not included in the tests. As observed, 0-degree results show disparities at $X_{LM} < 0.1$ and lower flow rates as explained already. However, increasing the flow rate to 600 kg/hr eliminates the negative deviations. For the 40-degree orientation, the results closely align with the 0-degree orientation and demonstrate overlap at different flow rates, which is desirable. Nevertheless, some negative deviations still exist at low X_{LM} , but less than 0-degree. Besides, the OR values and trends are very similar for 40-degree and vertical ones at $X_{LM} > 0.1$ (see Fig. 5 and 8).

In the case of 180-degree orientation, a strong correlation can be observed at lower X_{LM} values across various gas flow rates. However, discrepancies in response become apparent at X_{LM} values greater than 0.2. Additionally, this orientation shows a higher OR compared to other orientations. Fig. 9 provides a comparison between these three sensor orientations at the horizontal position and the vertical one at $X_{LM} < 0.1$.

The results for Coriolis Type B are illustrated in Figs. 10 & 11. As can be seen in these figures, in terms of the closeness of results at different gas flow rates, 90 and 40-degrees show better performance. However, when considering the linearity of response, OR values, and data scattering for the whole range of X_{LM} , the 40-degree orientation presents slightly better results. Additionally, by comparing the error bars at very high X_{LM} ($X_{LM} > 0.3$) it appears that the Coriolis prototype can better handle slug conditions at this angle compared to other angles.

It is evident that the 40-degree orientation outperforms the other orientations for both Coriolis prototypes in the horizontal position. Table 3 provides a more detailed comparison to understand the reasons behind this. The lowest OR across the entire range of X_{LM} can be observed at 40 degrees. Additionally, the least data scattering is seen at 90 and 40-degrees. The minimal data scattering at the 90-degree orientation can be attributed to the least interference of the tubes with the flow. However, the large OR at this orientation cannot be ignored. Regarding liquid distribution, 0 and 180-degrees show a symmetric distribution, while 40 and 90-degrees exhibit an asymmetric distribution. For instance, at the 90-degree orientation, one of the tube holes is at the bottom, and the other is at the top. This causes the liquid to flow more into the bottom hole (tube) due to higher density, while less liquid goes into the upper tube. Such an arrangement results in the bottom tube being filled with liquid and the upper tube with gas in certain flow patterns, such as slug and stratified. This can explain the least scattering of data at the 90-degree orientation in a slug flow pattern. Further data and considerations are needed to fully understand the details of this asymmetric liquid distribution.

However, the primary factor contributing to the superior performance of the 40-degree orientation can be attributed to the forces acting to push the liquid away from the Coriolis tubes. It is important to note that due to the structure of the Coriolis tube, there is always a possibility of liquid accumulation inside the tube, influenced by various parameters such as gas flow rate and flow pattern. The more liquid inside the tube, the greater the disturbance, which ultimately increases the OR for the gas flow. Therefore, a sensor orientation that can minimize this

behaviour would be preferable. As illustrated in Fig. 7(b), and disregarding interfacial shear forces, buoyancy and Coriolis forces, two forces act to move the droplets out of the tube and serve as driving forces (the gas driving force plus $mg \sin\theta$) in the downward section, while another force ($mg \cos\theta$) tries to retain the droplets within the liquid or near the wall surface [27], thereby increasing friction between the wall and the liquid. Consequently, the smaller the gravity force ($mg \cos\theta$), the easier it is for the liquid to flow through the tubes and exit on the other side. According to Table 3, the 40-degree orientation exhibits the lowest gravity force in the middle of tube, which is the most susceptible part to liquid accumulation. While it might be assumed that the 90-degree orientation offers a smoother path for liquid flow, as previously mentioned, this orientation suffers from a severe asymmetric flow condition. This means that the liquid predominantly flows through the bottom tube, while gas flows through the top, resulting in insufficient driving force supplied by the gas phase in the bottom tube where most of the liquid exists.

By comparing Figs. 5, 8 and 9, in terms of OR values and consistency of the response at different gas flow rates, vertical one and 40-degree shows priority over all other different orientations. However, the 40-degree response shows better consistency at different gas flow rates. It should be noted, that in terms of data scattering the vertical configuration is advantageous due to the lack of slug formation. Finally, it can be concluded that if the horizontal one was the only option, the 40-degree orientation would be preferred and if there is no limitation, the vertical one is the best choice due to frequency of annular flow pattern.

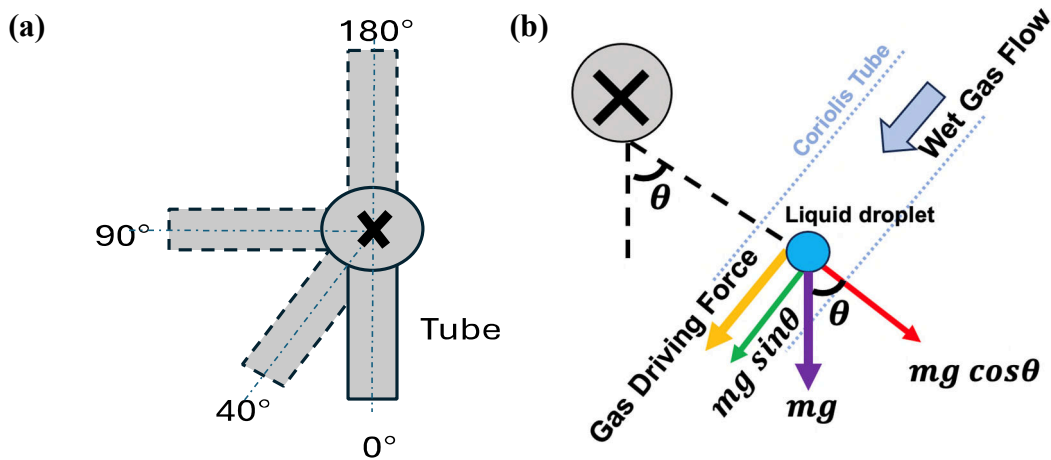


Fig. 7. (a) Flow view of different sensor tube orientations for Coriolis prototypes in a horizontal pipeline; (b) Main forces acting on a liquid droplet as the driving force and gravitational force ($mg \cos\theta$) in a downward part of 0-degree Coriolis.

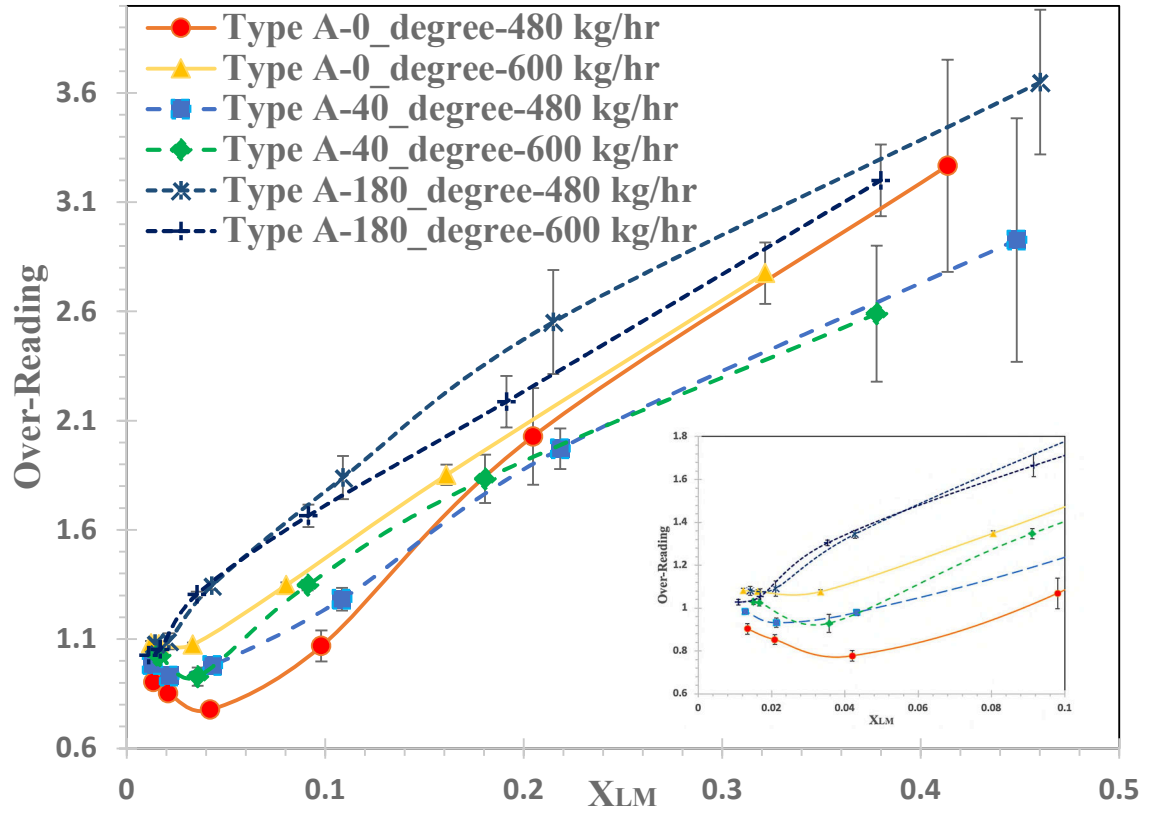


Fig. 8. OR of Coriolis Type A at various sensor angles in the horizontal position and line pressure 0.4 MPa.

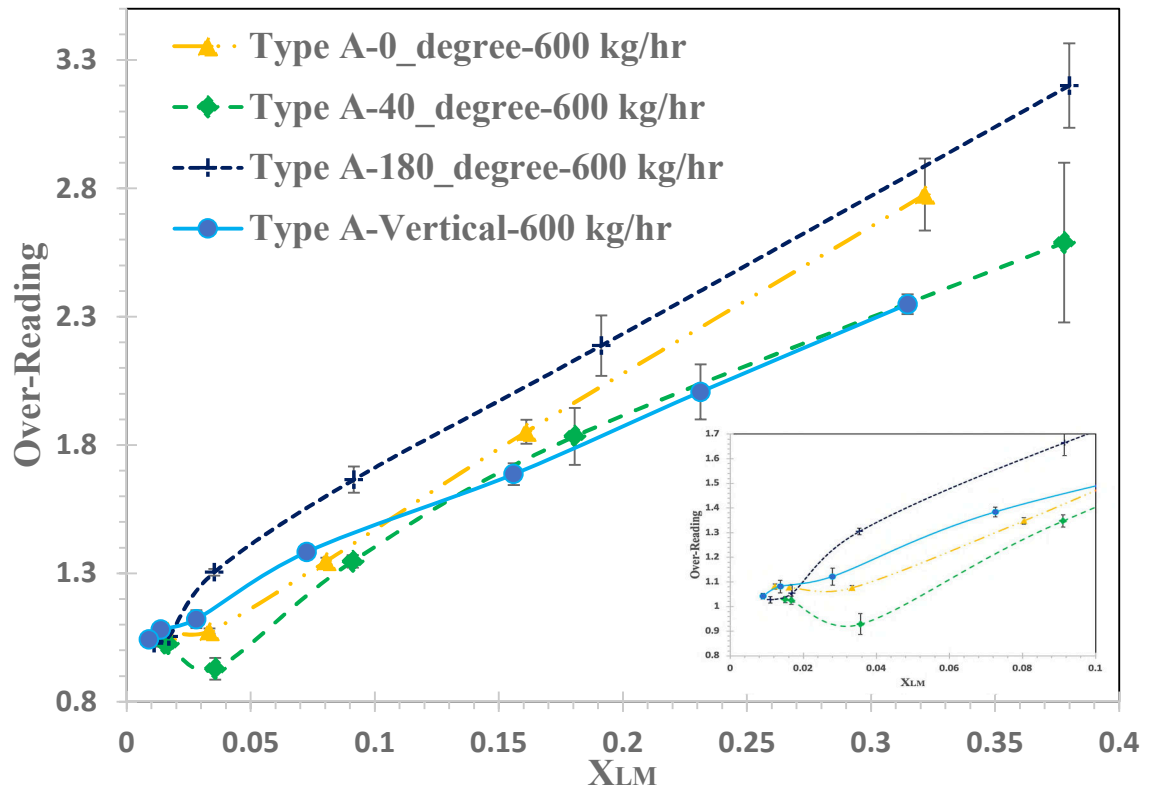


Fig. 9. Comparison of gas over-reading of Coriolis Type A at various sensor angles in both horizontal and vertical position and line pressure 0.4 MPa.

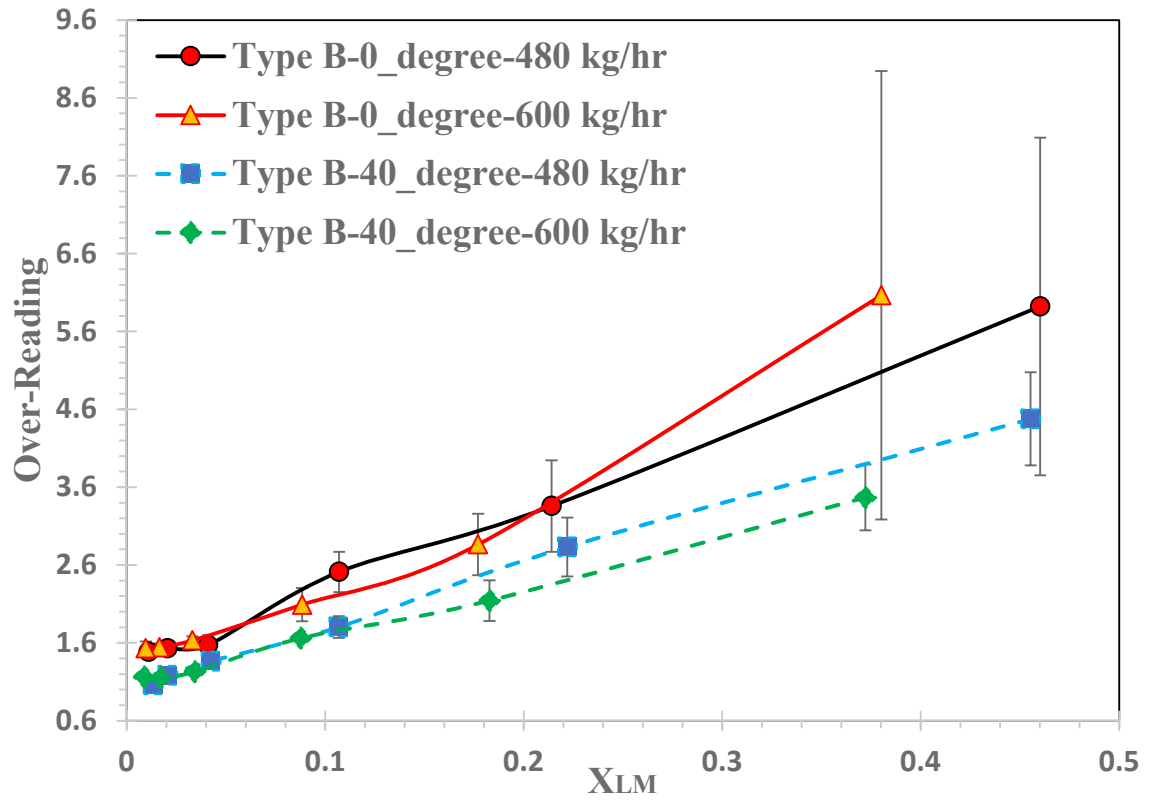


Fig. 10. Comparison of gas over-reading of Coriolis Type B at 0 and 40 degrees in the horizontal position and line pressure 0.4 MPa.

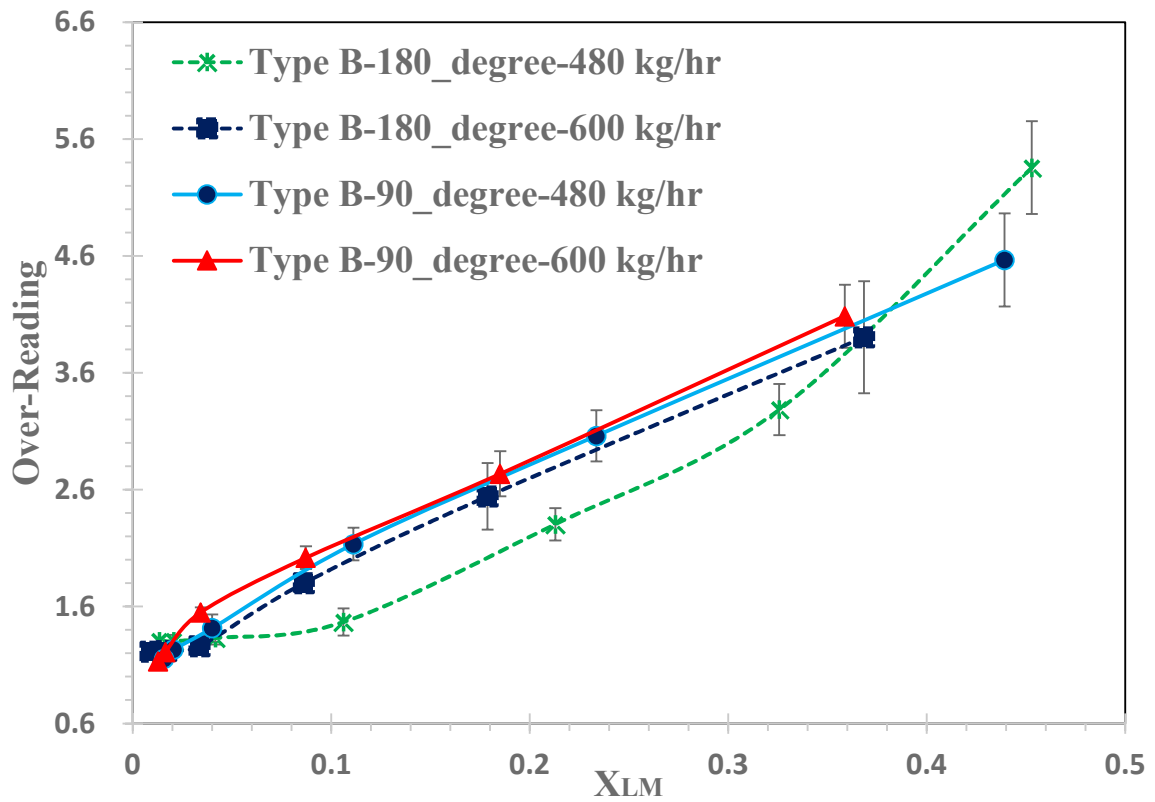
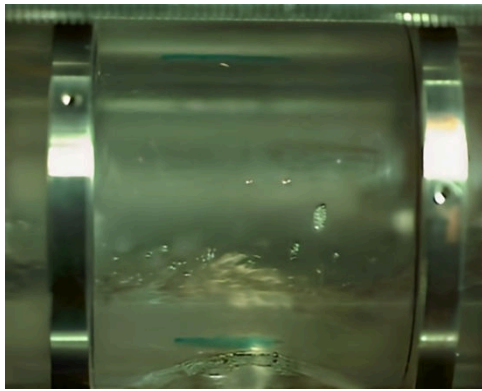
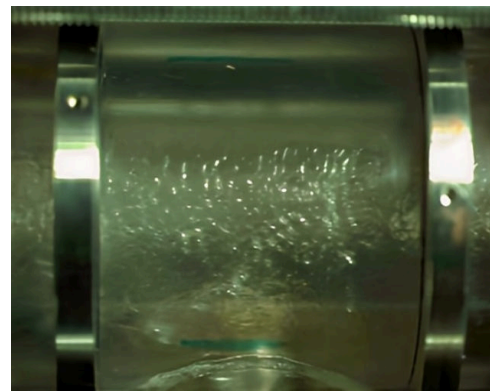
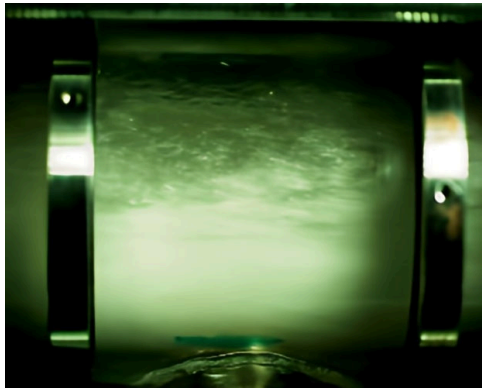
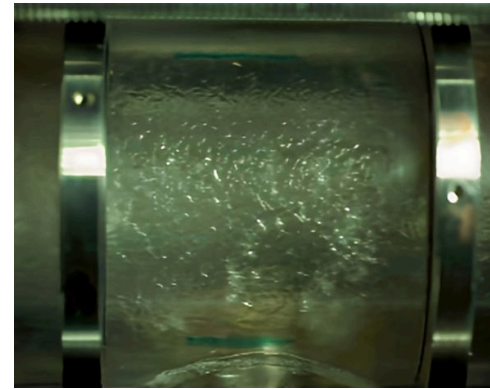


Fig. 11. Comparison of gas over-reading of Coriolis Type B at 90 and 180 degrees in the horizontal position and line pressure 0.4 MPa.

Table 3

Comparison of different sensor orientations in the horizontal position for Type B at 600 kg/hr gas flow rate.

Factor	0-degree	40-degree	90-degree	180-degree
OR _{avg.}	2.62	1.80	2.12	1.99
STD _{avg.}	0.610	0.139	0.114	0.165
Liquid distribution between two tubes	symmetric	asymmetric	asymmetric	symmetric
Gravity force at the middle of tubes	m _L g	0.76*m _L g	m _L g	m _L g

(a) Stratified Wavy; $U_{sg}=10.28 \text{ m.s}^{-1}$, $U_{sl}=0.039 \text{ m.s}^{-1}$ (b) Roll-Wave; $U_{sg}=19.21 \text{ m.s}^{-1}$, $U_{sl}=0.019 \text{ m.s}^{-1}$ (c) Slug; $U_{sg}=16.60 \text{ m.s}^{-1}$, $U_{sl}=0.296 \text{ m.s}^{-1}$ (d) Annular; $U_{sg}=24.88 \text{ m.s}^{-1}$, $U_{sl}=0.021 \text{ m.s}^{-1}$ **Fig. 12.** Main flow pattern of the wet gas in the horizontal configuration.

3.4. Flow pattern impact on response

An essential factor in the measurement of wet gas flows lies in the arrangement of liquid and gas components within a pipeline or flow pattern. As indicated in reference [2], the wet gas flow includes different flow patterns, such as annular, slug, stratified, and stratified wavy flow patterns in a horizontal pipe. In vertical pipes, churn and annular flow patterns are considered for the wet gas flow. The specific flow pattern observed depends on various factors such as gas and liquid flow rates, line pressure, pipe diameter, X_{LM} , etc. Additionally, certain transient conditions can be regarded as other flow patterns. For instance, in a horizontal pipe,

the semi-slug flow pattern may occur during the transition between slug and annular or slug and wavy flow patterns. Another example is the roll-wave flow, which indicates a transition between wavy and annular flow patterns [2,28].

For a fair comparison of various flow patterns' effects on the response of Coriolis meters, it is essential to compare the results under the same conditions. This can be achieved by mounting the Coriolis device in the vertical position and conducting tests under identical conditions. The setup primarily allows for the consideration of annular flow patterns in the vertical position, which can then be compared with various flow patterns in a horizontal pipe. However, under conditions of high wetness and low gas flow rates, the churn flow pattern will dominate in the vertical position. Before any comparisons, it is crucial to validate and confirm the accuracy of the considered flow patterns for each flow rate. Three distinct methods were employed for verification: 1) high-speed camera analysis, 2) Probability Density Function (PDF) assessment, and 3) a comparative analysis with existing literature reviews. An high-speed camera was utilized to capture detailed flow characteristics within the horizontal test section at a speed of up to 2000 frames per second (fps). Fig. 12 illustrates the main observed flow patterns. To validate these observed flow patterns, the wave signal of a conductance ring was employed to generate a Probability Density Function (PDF) profile. The output voltage is converted using the calibration curve acquired through static calibration. The normalized voltage was considered as:

$$NV = \frac{V_{out} - V_{min}}{V_{max} - V_{min}} \quad (6)$$

where NV is the normalized voltage, V_{min} and V_{max} are the output voltage when the pipe is full of air and water respectively, and V_{out} is the output voltage in the two-phase flow.

Some of the collected signals for observed flow patterns are presented in Fig. 13. As anticipated, there is a peak maximum observed in the slug flow pattern and a minimum in the stratified wavy pattern. The roll-wave behaviour falls in between the slug and annular flow patterns. A typical result of the PDF at different flow patterns is depicted in Fig. 14. In the PDF results, it is evident that each curve corresponds to a different flow pattern. The maximum peak at a very low liquid fraction resembles the stratified wavy flow pattern, while half of the maximum peak represents the annular flow pattern. The roll-wave flow pattern exhibits a maximum peak positioned between annular and slug flow patterns, including a broader range of liquid fractions. The PDF curve with the widest span of liquid fractions is associated with the slug flow pattern. These trends align with those reported in reference [29]. As a final validation step, all the observed flow pattern results in the horizontal position were compared with existing literature, demonstrating a very good agreement [28,30].

To compare various flow patterns, several tests were carried out by maintaining the liquid flow rate at a constant value while increasing the gas flow rate from 240 kg/hr to approximately 1000 kg/hr. Fig. 15 shows the results at a liquid flow rate of 0.2 kg/s within the X_{LM} range of 0.05-0.24. At higher liquid fractions ($X_{LM} > 0.1$) in the vertical position, the churn flow pattern can be considered [31], while in the horizontal position, stratified wavy flow and transitioning to roll-wave are observed. The horizontal flow patterns have been indicated in Fig. 15. The churn flow pattern exhibits greater results in terms of over-reading and data scattering. However, when it comes to transient conditions to roll-wave patterns, no obvious advantage can be identified. As the gas flow rate increases (resulting in a decrease in X_{LM}), the roll-wave flow pattern becomes apparent and eventually shifts to annular flow for the horizontal installation and vertical position. It was anticipated that the annular flow pattern in the vertical position would result in better performance for the Coriolis device due to a symmetrical distribution of flow compared to the horizontal annular pattern, which tends to be

unsymmetrical due to gravity. However, contrary to expectations, the horizontal installation demonstrates slightly better performance, at least in terms of data scattering. As previously explained, this may be related to the effect of the tube shape in the vertical position, where the tube is not entirely straight. Eventually, and from flow pattern analysis it can be concluded that the type of flow pattern alongside with the liquid fraction or wetness need to be considered. For example, the same stratified flow pattern at a very low liquid fraction exhibits different behaviour, with very low OR and data scattering (e.g., Fig. 4 (b)). Conversely, in slug flow patterns, a high liquid fraction combined with significant flow fluctuations leads to a high level of OR and data scattering, which is not observed in low wetness conditions.

This raises a question: which installation—vertical or horizontal—should be considered? To address this, two key factors must be taken into account. First, it's essential to develop a model that corrects the observed gas over-reading (OR). Second, this model should ideally be based on the internal parameters of the Coriolis prototype and be less reliant on flow patterns. Determining the OR is a crucial step in the model development. As explained already OR demonstrates a strong correlation with X_{LM} across different Coriolis prototypes in the vertical or horizontal position. Moreover, as it will be explained later, X_{LM} can be derived from the damping factor data of a Coriolis prototype. Fig. 16 illustrates a good correlation between OR and X_{LM} at different Fr numbers. Furthermore, based on the experimental tests, slug flow in the horizontal pipe causes severe scattering in the OR response. Therefore, choosing a horizontal installation may not be optimal due to flow pattern changes and their impact on the internal parameters of Coriolis. Consequently, to develop a correction model the vertical position was selected as the preferred installation, given its independence from flow patterns and potential for a more generalized approach. However, to ensure robustness, the model developed for the vertical section will also be extended to the horizontal position, with detailed results provided.

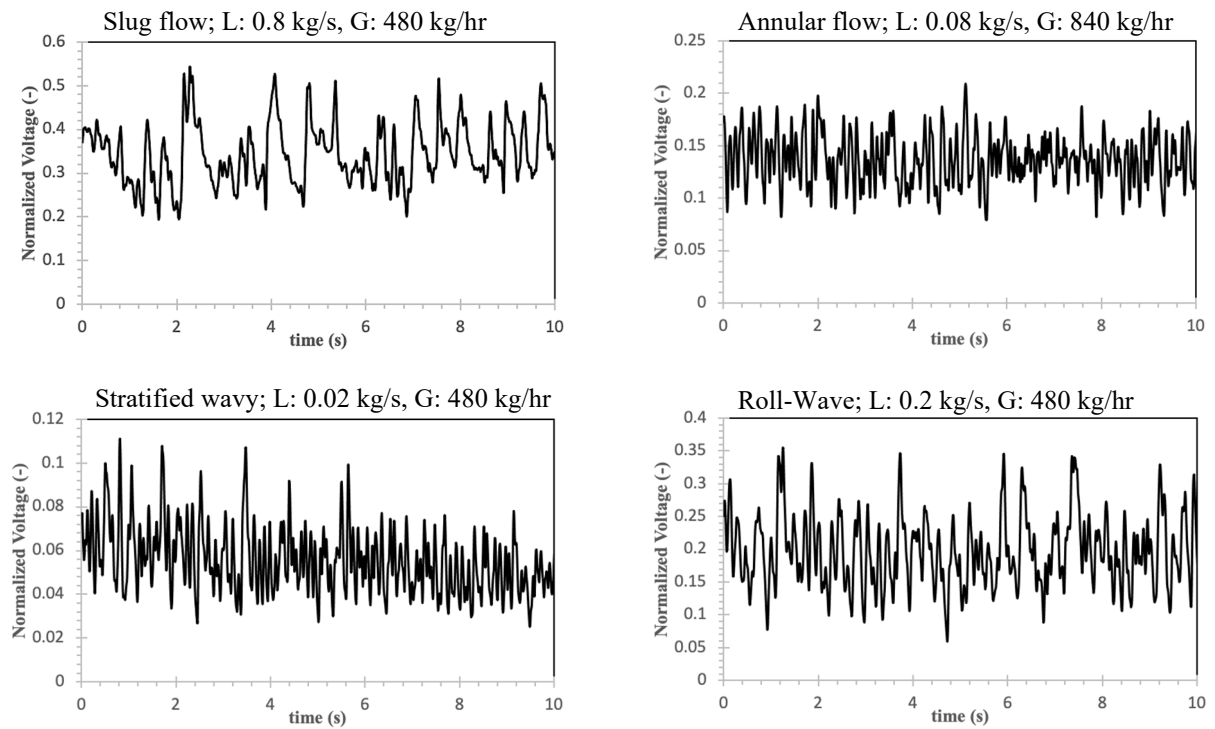


Fig. 13. Collected signals from horizontal water/air wet gas flow by the conductance sensor in (a) slug flow; (b) annular flow; (c) stratified wavy flow; and (d) Roll-wave flow patterns.

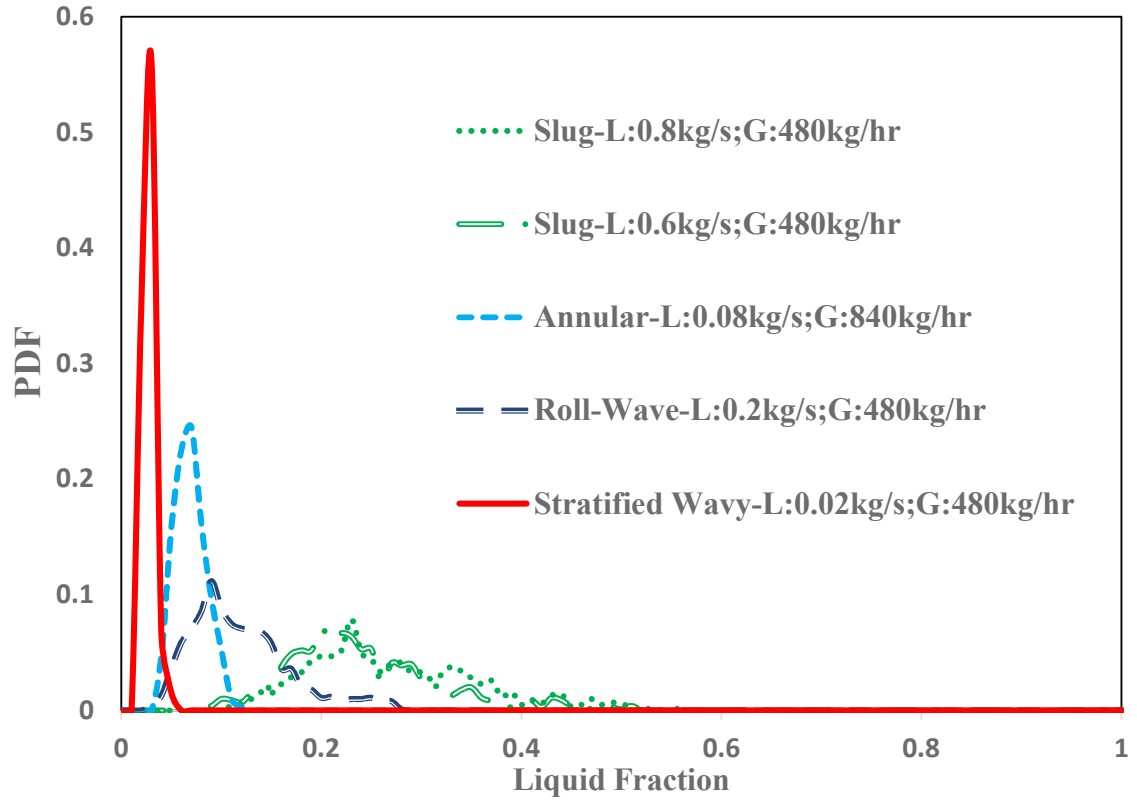


Fig. 14. Probability Density Function (PDF) for different flow patterns.

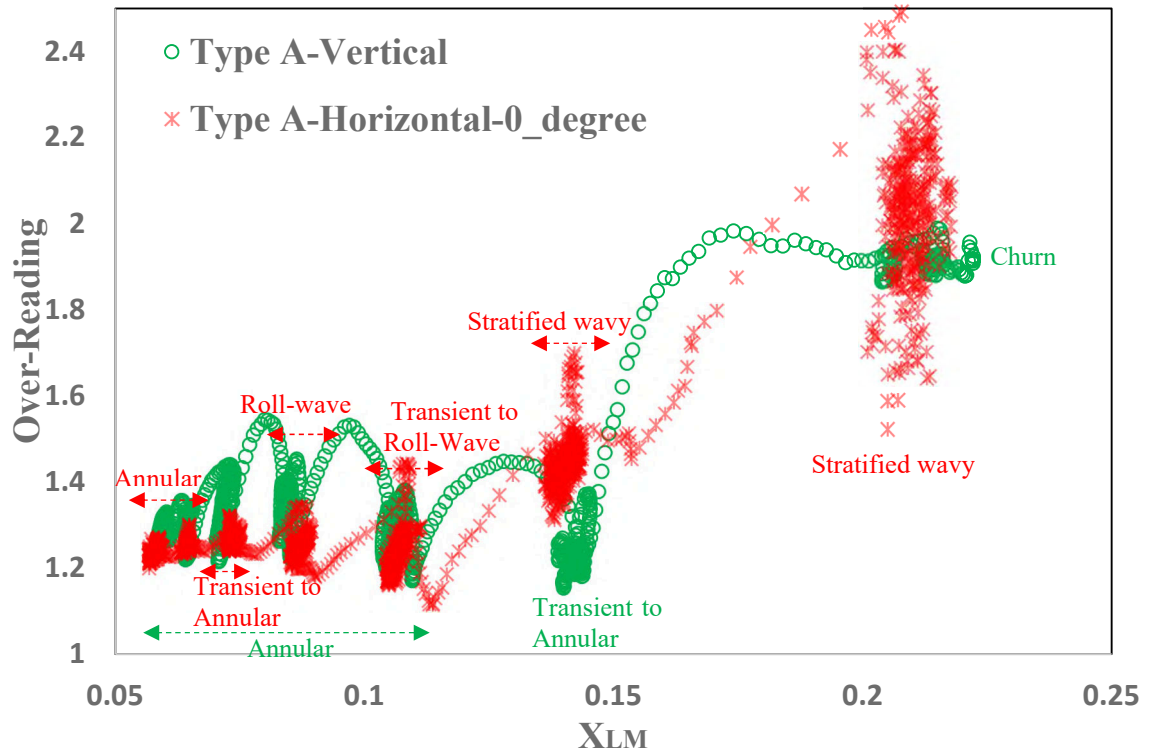


Fig. 15. Effect of different flow patterns in the vertical and horizontal (0-degree) positions at constant 0.2 kg/s liquid flow rate and varying gas flow rate 240-1000 kg/hr. The observed flow patterns in the horizontal and vertical positions are indicated in red and green, respectively (please refer to a colourful version).

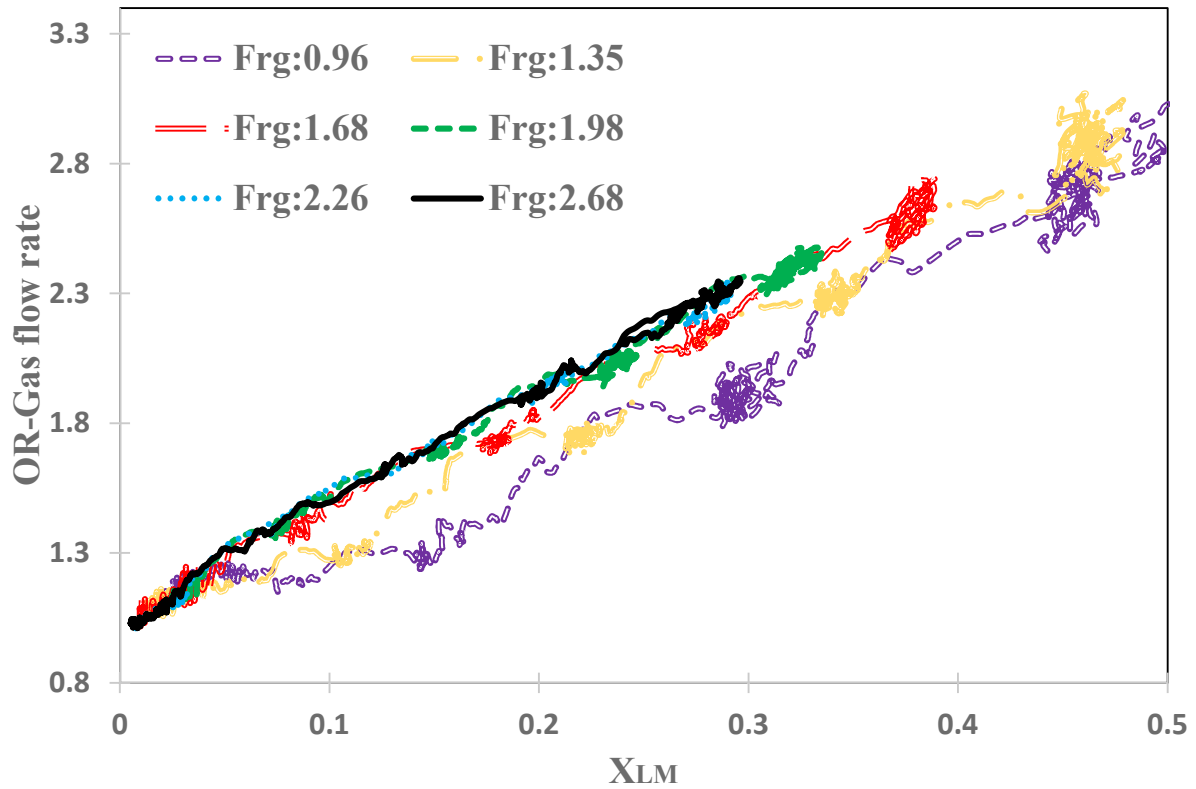


Fig. 16. Gas over-reading of Coriolis Type A versus X_{LM} at different Fr_g numbers in the vertical configuration and line pressure 0.4 MPa.

3.5. Analysis of wet gas results of Coriolis Type A in the vertical position

As has been already explained in the previous section, there is a good correlation between OR and X_{LM} in the wide range of gas flow rates (see Fig. 16). This correlation is very promising for the higher gas flow rates or $Fr_g > 1.6$ where the transition to an annular pattern occurs. However, by decreasing the gas flow rate there would be some deviations from the main trend. These deviations can be mostly attributed to the churn flow pattern in these regions. Since $Fr_g < 1.6$ is not that common in the industry, these deviations will be ignored, and the annular pattern will be considered as a dominant pattern in the vertical position. The assumption is that even by increasing the gas flow rate to the higher values, the trend will not change. Before that, X_{LM} needs to be estimated by using the damping factor data.

The damping factor is an internal parameter of Coriolis prototypes used in this study. It is defined as the ratio of exciter current to the oscillation amplitude of the Coriolis flow tube:

$$Df = \frac{I}{OA} \quad (7)$$

where Df is the damping factor, I and OA are the exciter current (A) and oscillation amplitude, respectively (m). The Coriolis prototype uses a control system to maintain the amplitude at a predefined value. To illustrate, if the oscillation amplitude is configured to a predefined value and, for various reasons (e.g., air contamination by denser fluids like water or oil), the oscillation falls below this threshold, the damping increases. Consequently, the exciter current

is raised to compensate for the higher damping. Therefore, the damping factor can serve as an indicator of the condition or characteristics of the medium. To make it more general, a reduced damping factor can be defined:

$$DfR = \frac{Df_{wet\ gas}}{Df_{dry\ gas}} \quad (8)$$

where DfR shows the two-phase flow damping factor. Fig. 17 illustrates a correlation between the reduced damping factor (DfR) and X_{LM} at various gas Froude numbers (Fr_g). Notably, X_{LM} can be identified as a function of the damping factor and gas Froude number. An increase in wetness leads to a rise in DfR and consequently X_{LM} . Different slopes are apparent at varying gas Froude numbers. However, at very low X_{LM} ($X_{LM} < 0.05$) and different gas Froude numbers, all curves converge to the same DfR and X_{LM} . In other words, at very low wetness, X_{LM} will change only by DfR . Furthermore, at higher gas flow rates ($Fr_g > 2.2$), different curves exhibit a similar trendline. It can be explained as in fully developed annular flow patterns, X_{LM} becomes independent of the gas Froude number and only varies with DfR . Therefore, X_{LM} can be related to these parameters simply as:

$$\begin{cases} X_{LM} = f(DfR, Fr_g), & Fr_g < 2.2 \\ X_{LM} = f(DfR), & Fr_g \geq 2.2 \end{cases} \quad (9)$$

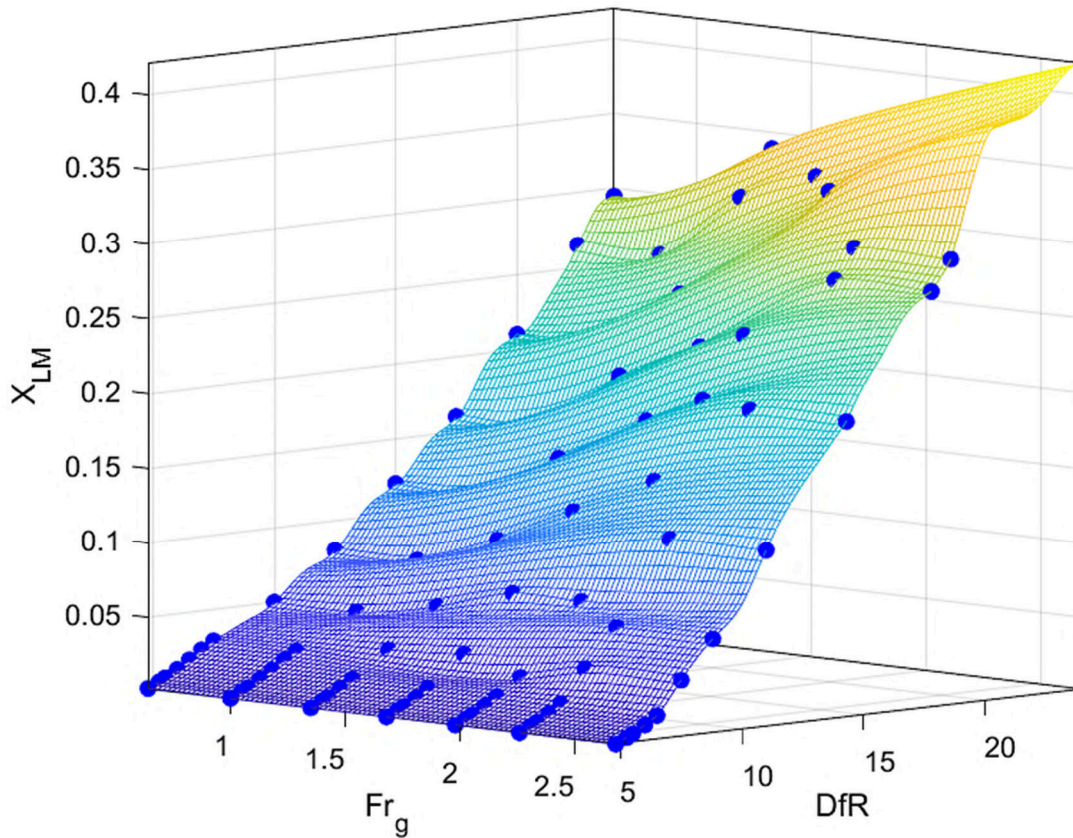


Fig. 17. X_{LM} as a function of Fr_g and DfR for the Coriolis Type A in the vertical configuration.

Eq. (9) has been classified as a multiple nonlinear regression problem. The best type of model fit was obtained through trial and error. The general form is as follows:

$$X_{LM} = \left(\frac{a_1}{\exp(Fr_g^{a_2})} \right) \times DfR^{1.8} + \left(\frac{a_3}{Fr_g^{a_4}} \right) \times DfR^{1.8} - a_5 \quad , \quad Fr_g < 2.2 \quad (10)$$

where a_1, a_2, a_3, a_4, a_5 are fitted coefficients and obtained using a least square method with an R-square of 0.992 and an average p-value of 0.00037. In this article, a_1, a_2, a_3, a_4, a_5 are -0.074416, 0.22815, 0.029139, 0.20873, and -0.026273, respectively.

At high gas Froud number ($Fr_g \geq 2.2$), the equation can be simply fitted using a polynomial with an R-square 0.999:

$$X_{LM} = -5 \times 10^{-5} DfR^3 + 0.022 DfR^2 - 0.0051 DfR - 0.0218 \quad , \quad Fr_g \geq 2.2 \quad (11)$$

To this point, X_{LM} has been obtained from Eq. (10) & (11) and we just need to develop a model to predict the OR. According to Fig. 16, there is a fair correlation between X_{LM} and OR at different gas Froud numbers. By applying a best fit, and ignoring the deviations at low Froude numbers, a correlation was obtained as follows:

$$OR = 10.7 X_{LM}^3 - 4.945 X_{LM}^2 + 4.74 X_{LM} + 0.9955 \quad (12)$$

The limitation is that when $X_{LM} \rightarrow 0$, OR should reach unity, a condition that has been satisfied with the fitted model. By calculating the OR and dividing the uncorrected mass flow rate by it, the actual gas mass flow rate can be obtained (Eq. (4)).

Another critical aspect of Coriolis meters is the total mass flow rate. The tubes detect and vibrate in response to the overall mass flowing through them. Fig. 18, displays the outcomes of total mass under-reading at various X_{LM} values. In other words, considering the dry gas an over-reading of mass flow rate can be observed and for the total mass flow rate an under-reading. The under-reading (UR) is determined as follows:

$$UR = \frac{\dot{m}_{g,unc.}}{\dot{m}_{g,Ref.} + \dot{m}_{l,Ref.}} = \frac{\dot{m}_{g,unc.}}{\dot{m}_{total}} \quad (13)$$

where $\dot{m}_{g,unc.}$ represents the uncorrected gas flow rate, and $\dot{m}_{l,Ref.}$ represents the flow rate of liquid from the reference meter, both in $\text{kg} \cdot \text{hr}^{-1}$. As depicted in Fig. 18, UR exhibits a distinct trend with the damping factor across a wide range of gas flow rates and X_{LM} . An average model is presented in Fig. 18 and was employed to establish the best fit using a sigmoidal function as follows:

$$UR = b_1 + \frac{(b_2 - b_1)}{(1 + (\frac{DfR}{b_3})^{b_4})} \quad (14)$$

where b_1, b_2, b_3 and b_4 are fitted coefficients and 1.0836, 0.3395, 10.4063, and -2.4733, respectively. It's worth noting that for damping factors exceeding 7500, where slug flow prevails, UR remains constant and does not vary with the damping factor. In other words, the damping factor becomes saturated in this region. A similar pattern has been reported for the drive gain in the Coriolis meters [32], and this aspect should be taken into account for future

model developments. By determining the gas flow rate and now the total mass flow, the liquid flow rate can be easily calculated:

$$\dot{m}_l = \dot{m}_{total} - \dot{m}_g \quad (15)$$

where $\dot{m}_l$ is the liquid flow rate, $\dot{m}_{total}$ total mass flow rate and $\dot{m}_g$ corrected gas mass flow rate. This establishes a method for estimating the liquid flow rate. The second approach involves applying the definition of X_{LM} . Given that X_{LM} has been derived from the gas flow algorithm, it can be utilized to determine the liquid flow rate by rearranging Eq. (5):

$$\dot{m}_l = X_{LM} \cdot \dot{m}_g \cdot \sqrt{\frac{\rho_l}{\rho_g}} \quad (16)$$

Percentage error (PE) and mean absolute percentage error (MAPE) are employed to assess the accuracy of model in predicting gas and liquid flow rates, which are defined by the following equation:

$$PE(j) = \frac{\dot{m}_{model}(j) - \dot{m}_{Ref.}(j)}{\dot{m}_{Ref.}(j)} \times 100 \% \quad (17)$$

$$MAPE = \frac{1}{N} \sum_{j=1}^N [abs(PE(j))] \times 100 \% \quad (18)$$

where $\dot{m}_{model}$ and $\dot{m}_{Ref.}$ show the predicted gas or liquid mass flow rate from the wet gas model and gas or liquid mass flow rate from the reference meters, respectively.

Fig. 19 illustrates typical results at a gas flow rate of 840 kg/hr and compares the outcomes of total mass-based and X_{LM} -based approaches for liquid flow rate measurement. Remarkably, the total mass-based method exhibits negative errors, while the X_{LM} -based method shows almost positive errors at $X_{LM} > 0.1$. Leveraging this difference, both methods can be advantageous for acquiring a more accurate prediction of the liquid flow rate. To achieve this, a weight factor for each method was defined, and the average value of the liquid flow rate was subsequently calculated:

$$\dot{m}_{l,avg} = \left(\frac{w_1 \cdot \dot{m}_{l,total\ mass-based} + w_2 \cdot \dot{m}_{l,X_{LM}-based}}{w_1 + w_2} \right) \quad (19)$$

where w_1 and w_2 represent the weight coefficient for total mass-based and X_{LM} -based, respectively. Considering the whole range of gas flow rates, the best approach was obtained by implementing a weight factor of 2 for the total mass-based and 1 for the X_{LM} -based. At $X_{LM} < 0.1$ the results from the total mass-based approach proved to be superior, presenting the use of the X_{LM} -based method unnecessary in this range.

3.6. Wet gas two-phase flow model using Coriolis Type A

Up to this point, X_{LM} , OR, total mass, and liquid flow rate were determined only based on the damping factor data. However, there remains an unresolved issue: the lack of knowledge regarding the correct value for Fr_g . This prevents us from proceeding to calculate X_{LM} from Eq. (9). To address this, we require an initial estimation of Fr_g which can be denoted as

uncorrected Fr_g ($Fr_{g,unc}$). By using this value in conjunction with the damping factor data, we can determine the appropriate model to obtain X_{LM} . According to experimental data it can be mentioned if each one of the below conditions satisfies, then the real Fr_g should be less than 2.2 and we can choose the correct model to obtain X_{LM} :

$$\left\{ \begin{array}{l} \text{if } DfR \geq 15 \text{ and } Fr_{g,unc} \leq 4.2 \rightarrow \text{High wetness } (X_{LM} > 0.2) \\ \text{if } 10 \leq DfR < 15 \text{ and } Fr_{g,unc} \leq 3.2 \rightarrow \text{Medium wetness } (0.1 < X_{LM} < 0.2) \\ \text{if } 2 \leq DfR < 10 \text{ and } Fr_{g,unc} \leq 3.2 \rightarrow \text{Low wetness } (X_{LM} < 0.1) \end{array} \right. \quad (20)$$

With the notation provided, a wet gas model can be constructed for the Coriolis Type A using an iterative algorithm to accurately estimate gas and liquid flow rates. The algorithm procedure is illustrated in Fig. 20. Each step can be explained as:

Step 1: Obtaining the temperature, pressure, damping factor, and uncorrected mass flow rate ($m_{g,unc}$).

Step 2: Calculate DfR and gas and liquid density. The assumption is that the types of liquid and gas are already known.

Step 3: If $DfR > 2$, there exists a wet gas flow and we need to go ahead with the wet gas model.

Step 4: Calculate $Fr_{g,unc}$ from Eq. (2) and use DfR to see if they satisfy the conditions in Eq. (20). If yes, use Eq. (9) to calculate the X_{LM} , otherwise applying Eq. (10).

Step 5: Calculate the $OR_{g,c,i-1}$ from Eq. (12) as a first iteration for the corrected OR.

Step 6: Calculate $\dot{m}_{g,c,i-1}$ from Eq. (4) as the first iteration of obtaining gas mass flow rate.

Step 7: Calculate $Fr_{g,c,i}$ from Eq. (2) as a corrected gas Froud number. And then based on conditions in Eq. (20), calculate $X_{LM,c,i}$.

Step 8: Using Eq. (12) to calculate $OR_{g,c,i}$ and then $\dot{m}_{g,c,i}$.

Step 9: Continue the iteration until the absolute error between $\dot{m}_{g,c,i}$ (new) and $\dot{m}_{g,c,i-1}$ (past) becomes less than the defined tolerance (here 0.01), then finish the iteration and converge the corrected gas mass flow rate and X_{LM} .

Step 10: Using obtained X_{LM} and $\dot{m}_g$ to calculate the liquid flow rate from Eq. (16).

Step 11: Applying Eq. (13) to obtain the UR.

Step 12: Calculate the total mass flow rate from Eq. (13) by dividing the uncorrected mass flow rate to UR.

Step 13: Provide an average of the liquid flow rate based on Eq. (19) for $X_{LM} > 0.1$ and use just the liquid flow rate from the total mass-based if $X_{LM} < 0.1$.

Fig. 21-24 presents the model results for the vertical Coriolis. Fig. 21 & 22 illustrate the prediction of gas and liquid flow rates using the wet gas model under churn flow pattern condition. Analysing Fig. 21, it is evident that as the gas flow rate increases from 360 kg/hr to 600 kg/hr, errors decrease, and data scattering diminishes. Since deviations in the lower gas flow rate from the main OR curve (Fig. 16) were obvious, the errors in these flow rates were expected. For a higher gas flow rate (600 kg/hr), all the PE falls within the range of $\pm 5\%$. This observation can be attributed to the churn flow pattern, where an increase in gas flow rate results in a smoother liquid film, preparing to transition into an annular flow pattern. Furthermore, a noticeable reduction in error is observed with a decrease in the X_{LM} . At $X_{LM} < 0.1$, over 97 % of sampling points fall within the range of $\pm 10\%$. Since the calculation of the liquid flow rate is dependent on gas flow rate data, the same trends can be seen for the liquid flow rate in the churn flow pattern and most of the errors fall within $-15 - 5\%$ (Fig. 22). The

Mean Absolute Percentage Error (MAPE) for the entire range of X_{LM} is 7.1 % for the gas flow rate and 11.7 % for the liquid flow rate.

The results for the annular flow pattern are illustrated in Fig. 23 & 24. The model demonstrates enhanced model accuracy for both gas and liquid flow rates under this condition. Remarkably, the error analysis reveals that, for gas flow rate 95 % of error data fall within the range of ± 7.5 % across the entire range of X_{LM} with the standard deviation of the percentage error (uncertainty) 2.7 %. The MAPE of the gas flow rate for the entire range is 3.9 %.

Similarly, when considering liquid flow rate, an error margin of ± 10 % is evident throughout 87 % of the data and the entire range of X_{LM} . The MAPE for the entire range is 4.3 % for the liquid flow rate. This signifies an excellent predictive capability of the model under the annular flow pattern condition.

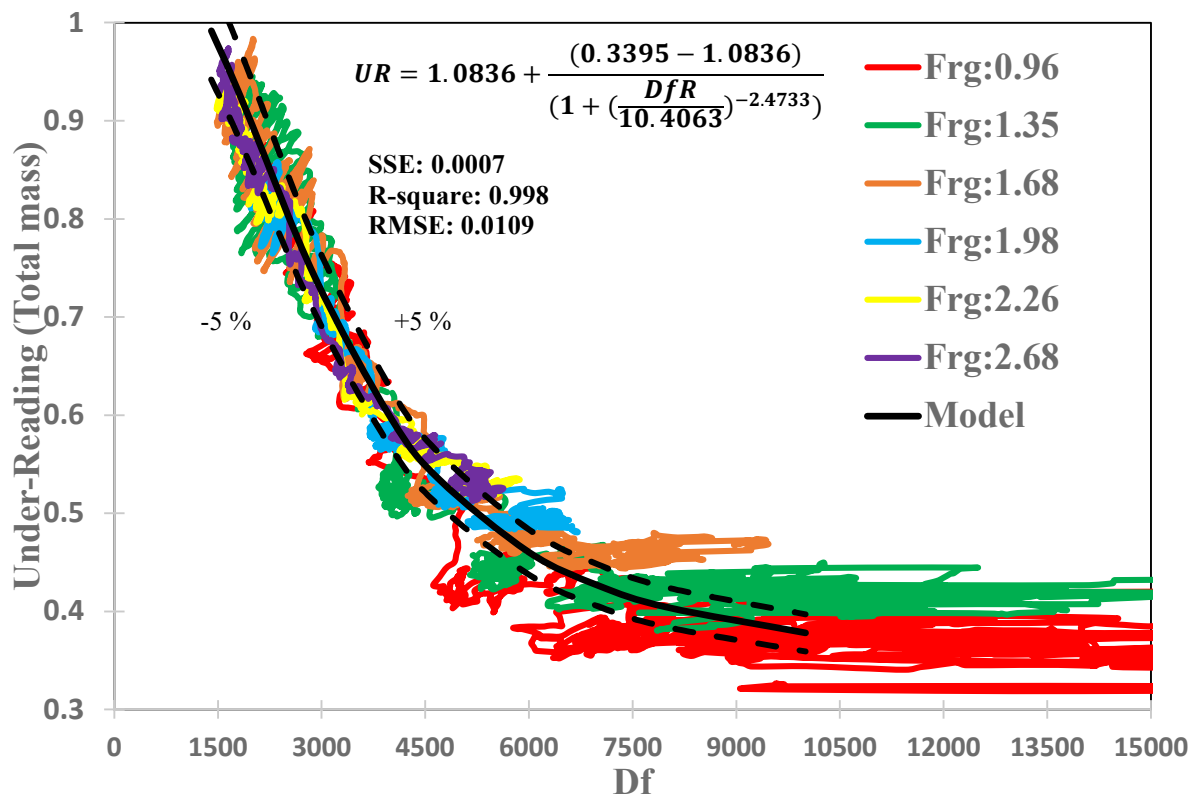


Fig. 18. Under-Reading of Coriolis Type A at different gas Froude numbers in the vertical configuration.

3.7. Robustness analysis of the wet gas model

For a model to be considered reliable, it must exhibit robustness in its predictions. Robustness implies the ability of the model to precisely estimate flow rate under various conditions, including mechanical stress such as pulsations and vibrations, temperature fluctuations, high pressures, abrasion, different media types, over-speeding, different pipe sizes, and different flow patterns. Due to limitations, it is impractical to test the model under all conceivable conditions. However, we aim to evaluate and compare the model using literature data to the extent possible. Initially, the model was tested against another Coriolis device installed in the horizontal position, experiencing different flow patterns [24]. The results, as depicted in Fig. 25, demonstrate excellent performance across various flow patterns, except for the slug flow. For X_{LM} values less than 0.3, 92 % of sampling points fall within the ± 5 % relative error band. Deviations observed during slug flow were predictable due to high wetness and flow fluctuations. The averaging method can help mitigate issues related to slug

flow and data point scattering and enhance accuracy, as formerly was suggested for the Coriolis meters [9,33]. Overall, it can be concluded that the model performs well across different flow patterns and configurations.

Additionally, reference [9] provided data on wet gas flow using a long-tube U-shape Coriolis meter with natural gas at varying oil loadings. The experiments were conducted in a horizontal 4-inch pipe with gas flow rates ranging from 1800 to 14400 kg/hr. However, the specific configuration of the Coriolis meter was not specified. Given the high gas flow rate, it's likely that an annular flow pattern was observed during their tests. Fig. 26 compares the results from this reference with the findings of the present study. Despite significant differences such as a substantial line pressure difference (2.5 MPa for the reference and 0.4 MPa for this study), variations in liquid and gas types, differences in the type of Coriolis meter used (long-tube in their work and short-tube in ours), different pipe sizes (4-in versus 2-in), and even differences in the positions of the two Coriolis, a similar trend can be observed in the results. Indeed, the values are nearly identical in both cases. However, some differences were observed at very high pressure (5 MPa) [9].

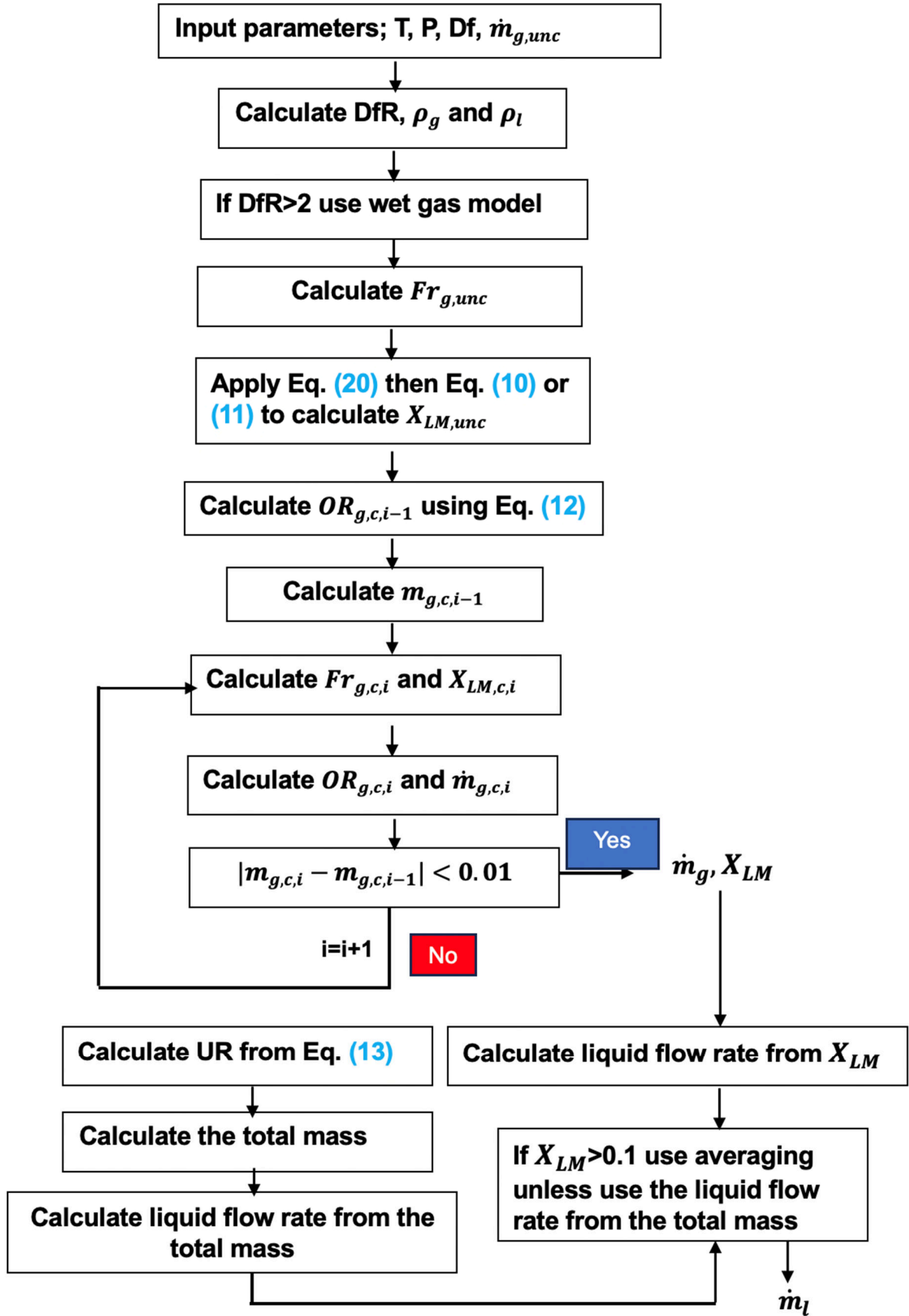


Fig. 20. Flowchart of gas and liquid flow rate measurements in the wet gas flow for the Coriolis Type A.

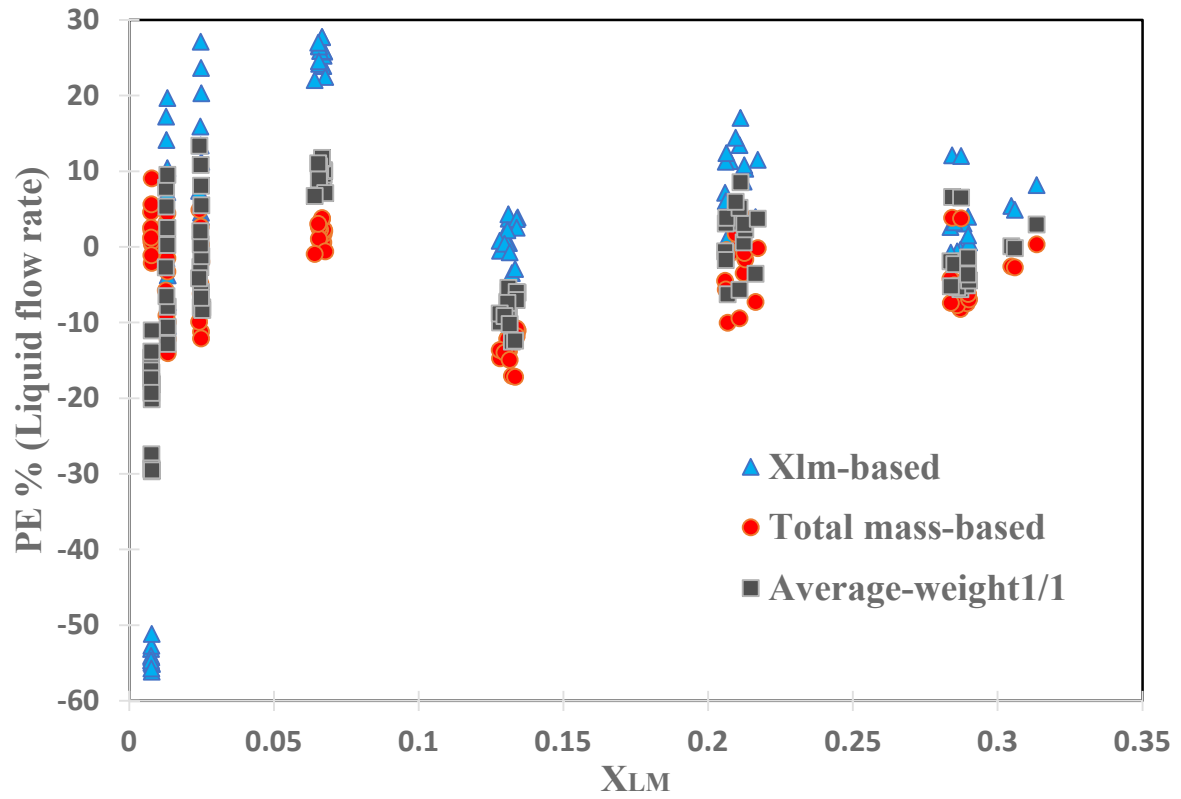


Fig. 19. Comparison of calculated liquid flow rate using X_{LM} -based and total mass-based methods and their equal average at a gas flow rate of 840 kg/hr.

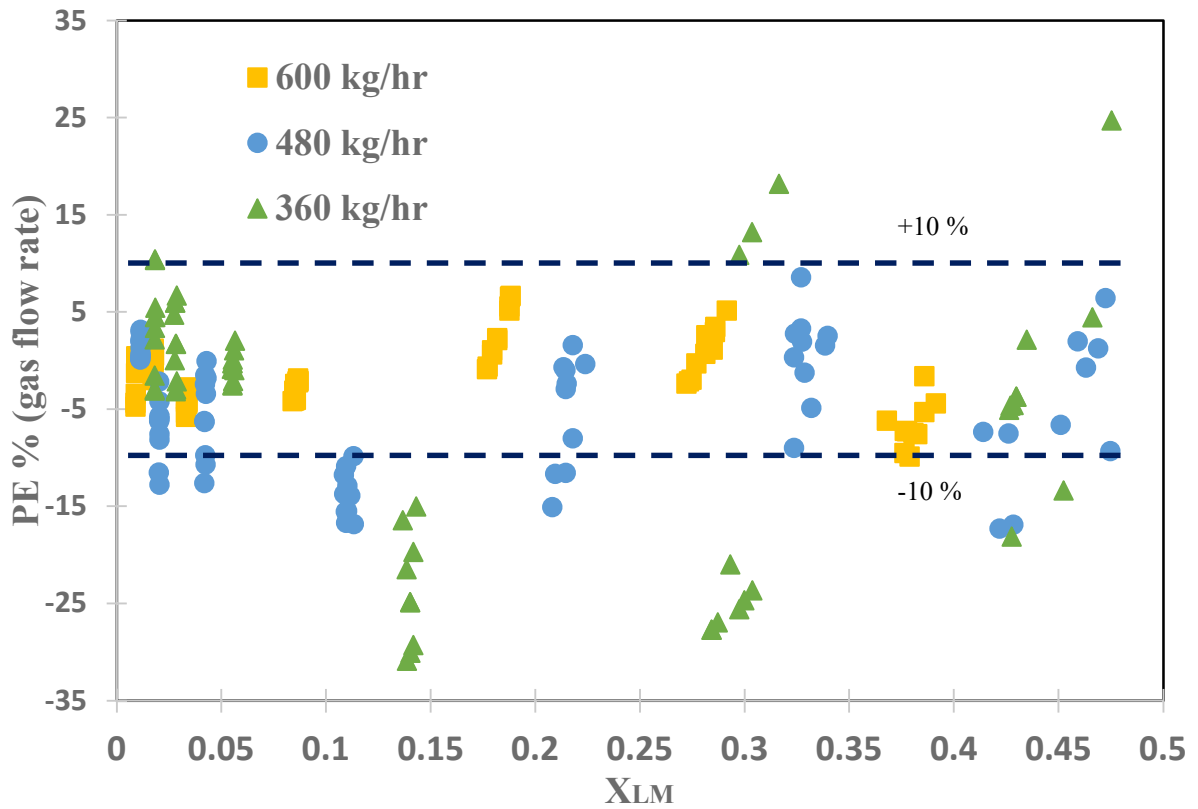


Fig. 21. Relative error of gas mass flow rate prediction in the churn flow pattern.

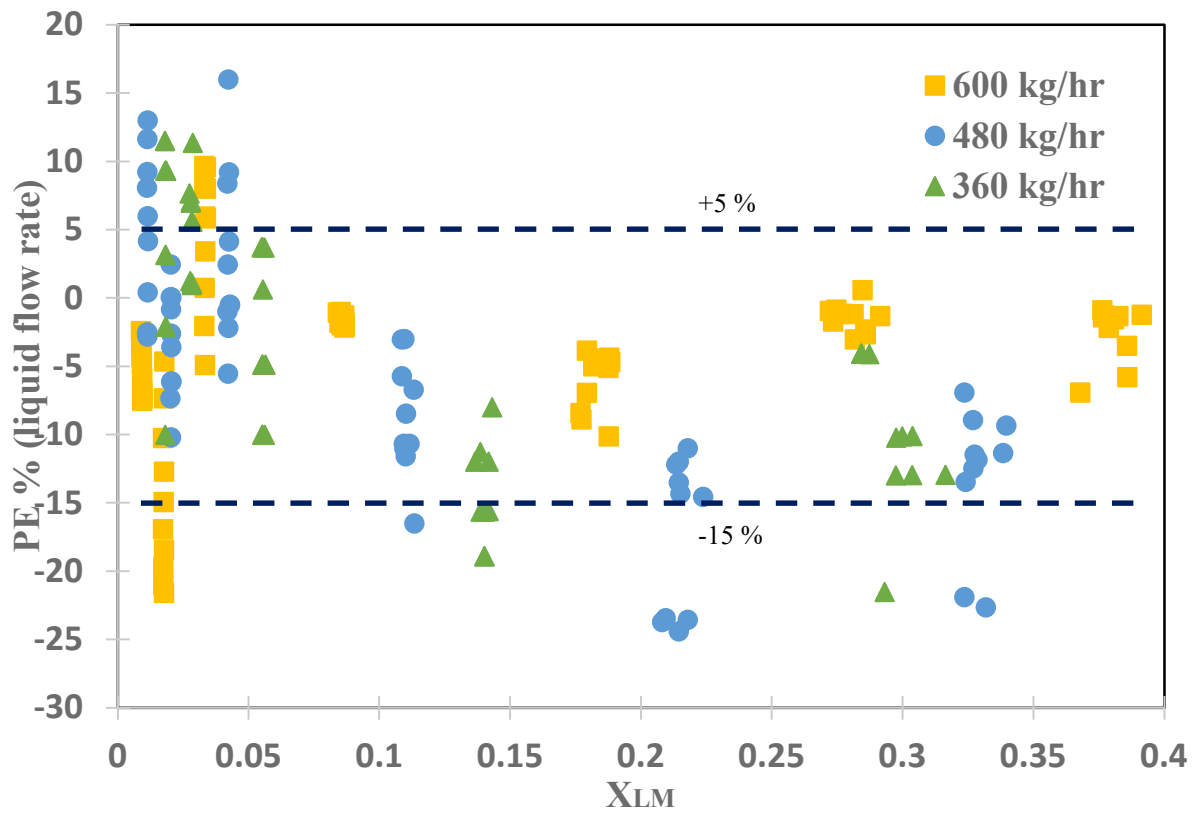


Fig. 22. Relative error of liquid flow rate prediction in the churn flow pattern.

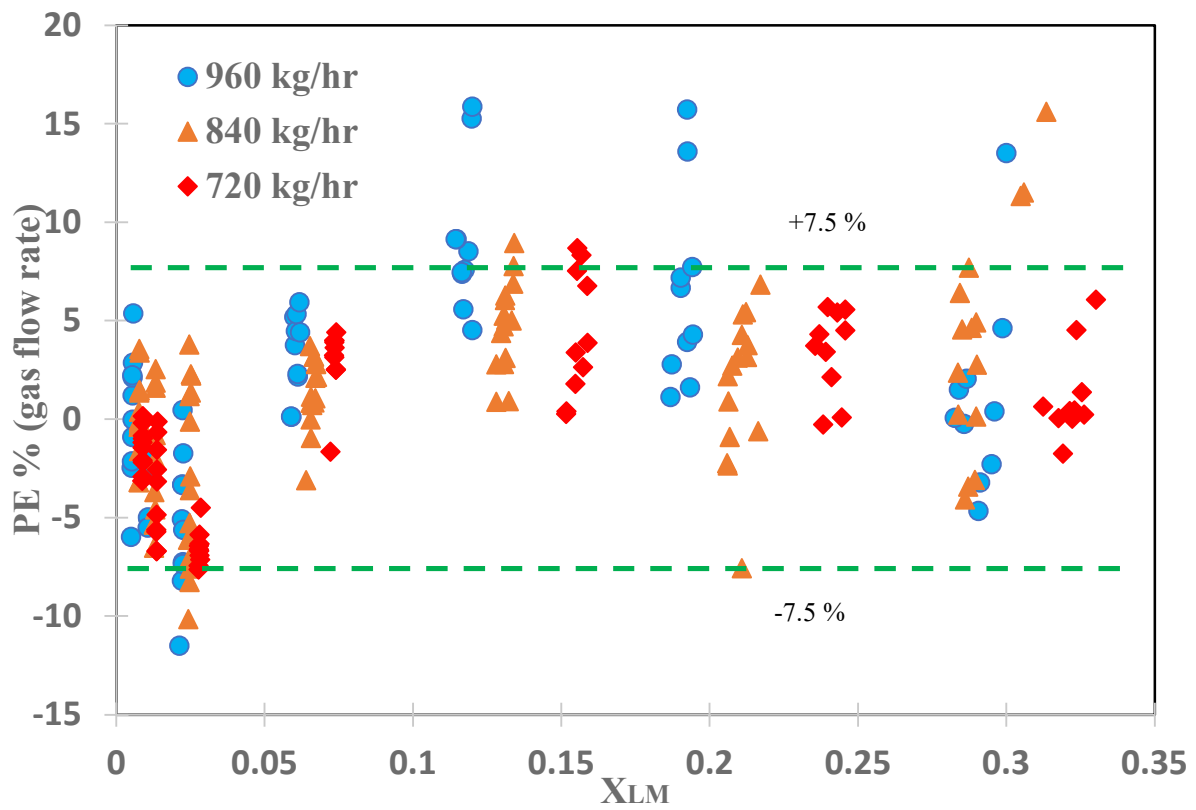


Fig. 23. Relative error of gas mass flow rate prediction in the annular flow pattern.

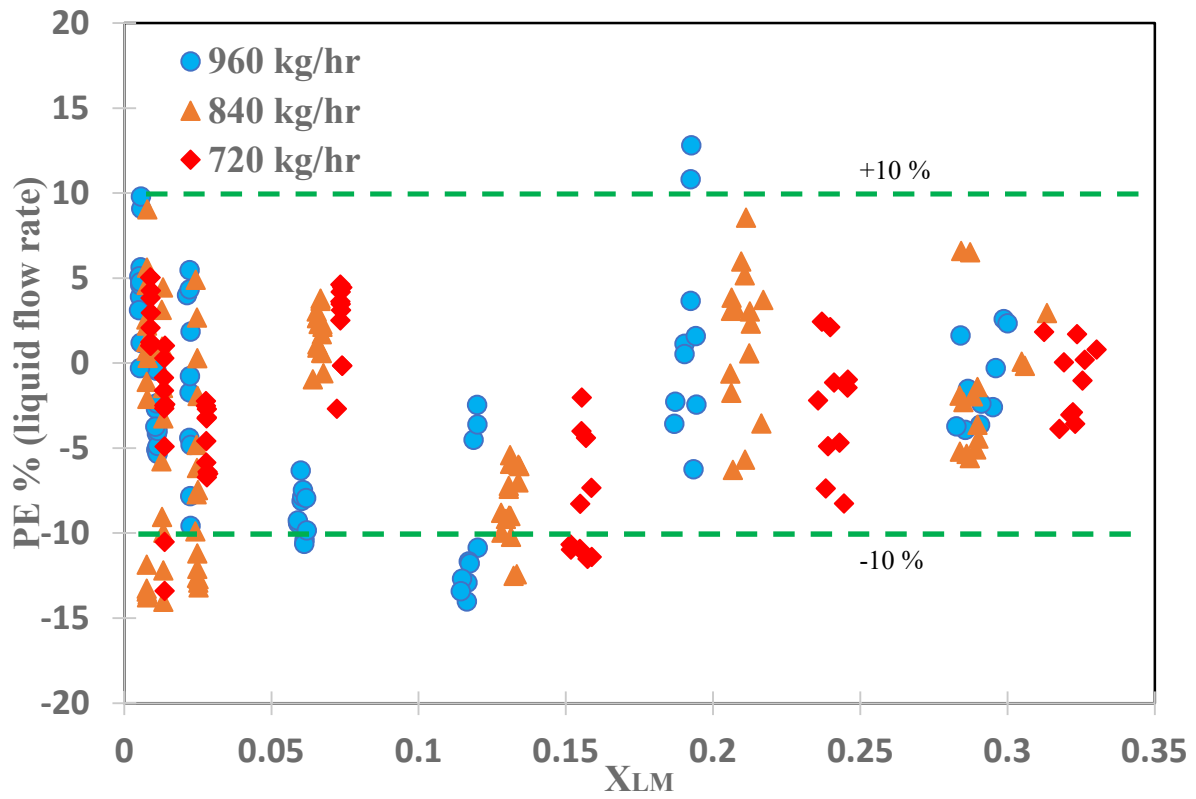


Fig. 24. Relative error of liquid mass flow rate prediction in the annular flow pattern.

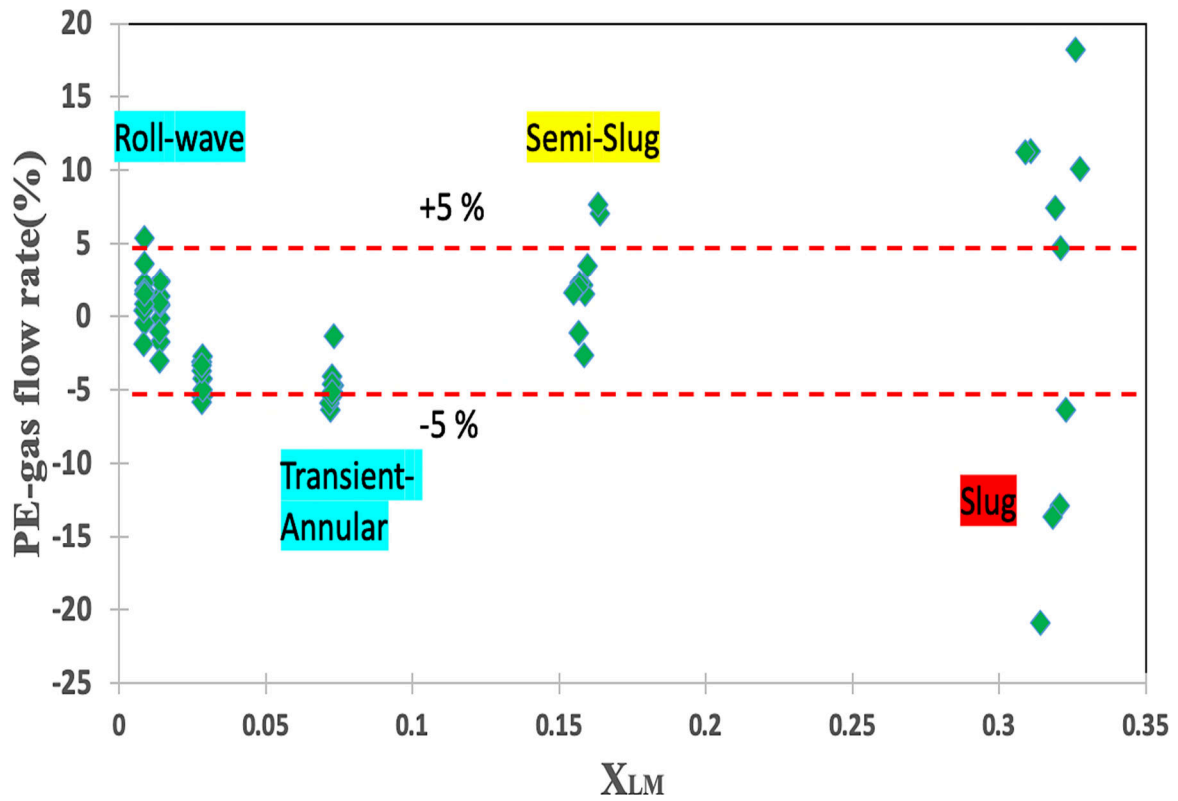


Fig. 25. Results of tested model for a different Coriolis in the horizontal position at 720 kg.hr⁻¹ gas flow rate.

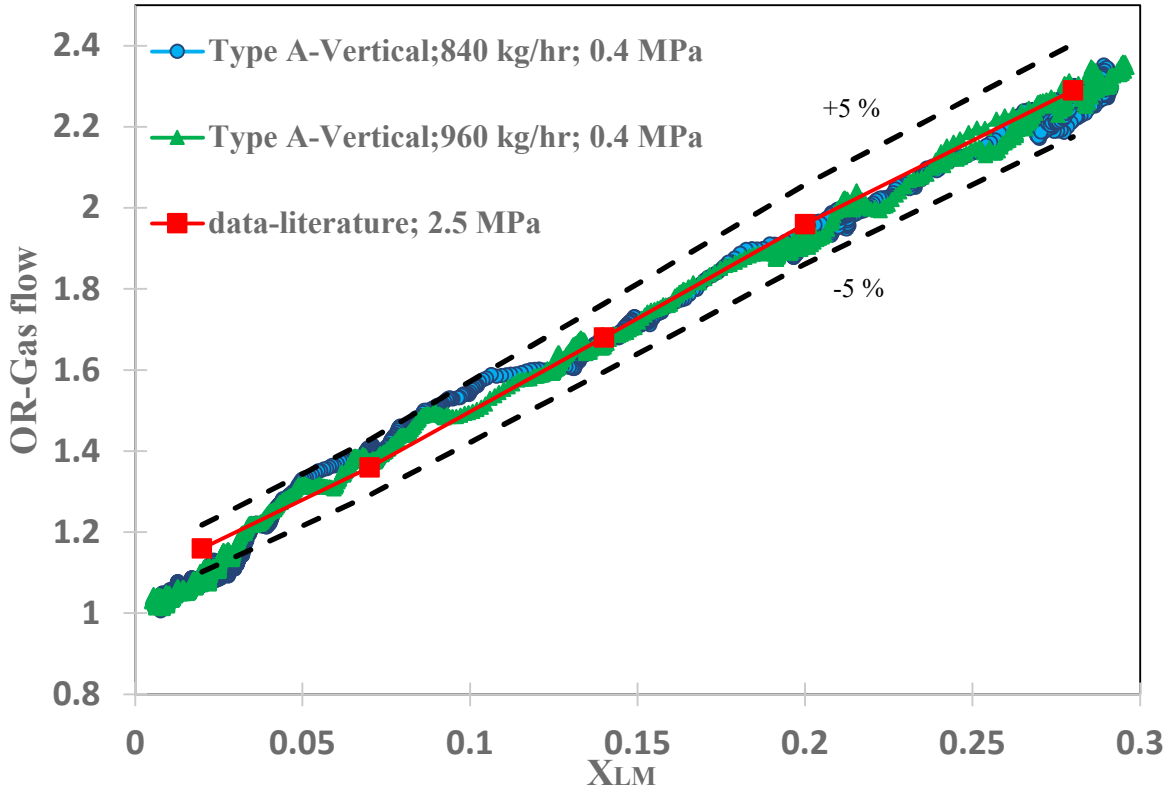


Fig. 26. Comparison of gas OR results with the literature [9].

4. Conclusion

This study employed two distinct Coriolis prototypes to measure wet gas flows. A comprehensive exploration was conducted, involving the examination of the effect of vertical and horizontal pipelines, and different sensor tube angles on the wet gas metering performance. Subsequently, a wet gas model was developed to measure the gas and liquid flow rates. The primary research contents and conclusions are outlined as:

- Two different Coriolis prototypes were studied. The investigation revealed they have exhibited different performance in wet gas flow, particularly in terms of gas over-reading and data scattering.
- Regarding various sensor tube angles in the horizontal pipeline, the best results were observed across both Coriolis prototypes at a 40-degree angle. At this angle, a notable linear correlation was identified at different gas Froude numbers. This correlation is crucial for the development of a robust model.
- By comparing the vertical and horizontal results for a Type A Coriolis, both vertical and 40-degree in the horizontal position exhibit closely matched results and better performance compared to other installations in terms of OR and data consistency.
- When comparing flow patterns in both vertical and horizontal positions, slug flow exhibits the most significant deviations for both Coriolis prototypes, affecting both Over-Reading (OR) and data scattering. It's important to note that under conditions of high liquid fraction, the liquid loading becomes as significant as the flow pattern. Interestingly, under the same high liquid fraction, the vertical position with an annular

pattern demonstrates less data scattering. In situations where the liquid fraction is low ($X_{LM} < 0.1$), horizontal flow patterns such as stratified wavy, roll-wave, and annular patterns exhibit less data scattering. Conversely, for higher liquid fractions ($X_{LM} > 0.1$), the vertical position proves to be more advantageous. Lastly, when dealing with a broad range of X_{LM} values, adopting a vertical position becomes a more reasonable choice due to a lack of slug formation. This highlights the importance of considering both the liquid fraction and flow patterns when determining the optimal measurement setup.

- A strong correlation was identified between the gas OR and X_{LM} at different gas Froude numbers for prototype A in the vertical position. Similarly, a noteworthy correlation was observed for the under-reading of total mass and damping factor. Leveraging these correlations, a new wet gas model was proposed for the prototype A.
- Under churn flow patterns, the model shows a PE of $\pm 10\%$ for the gas flow rate and primarily from -15% to 5% for the liquid flow rate. The Mean Absolute Percentage Error (MAPE) for the entire dataset is 7.1% for the gas flow rate and 11.7% for the liquid flow rate. In scenarios involving higher Froude numbers and annular flow patterns, which is more common, the PE is $\pm 7.5\%$ for gas flow rate and $\pm 10\%$ for liquid flow rate with a 95% confidence level. The MAPE for the entire range is 3.9% for the gas flow rate and 4.3% for the liquid flow rate with an uncertainty of 2.7% . These results highlight the effectiveness of the suggested wet gas model under various flow conditions.

CRedit authorship contribution statement

Seyed Milad Salehi: Conceptualization, Writing - original draft, Writing - review & editing., **Liyun Lao:** Conceptualization, Supervision, Writing - review & editing., **Nigel Simms:** Supervision, review & editing., **Wolfgang Drahm:** Funding acquisition, Supervision., **Yaoying Lin:** Conceptualization, Supervision, Writing - review & editing., **Alfred Rieder:** Conceptualization, Supervision, Writing - review & editing., **Andreas Güttler:** Conceptualization, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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