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Response of A Coriolis Gas Flow Meter to Steady and Transient Wet Gas Flow Conditions

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Abstract – Coriolis devices are continuously evolving to meet the demands of different conditions, such as wet gas flow. However, their application in wet gas flow has not yet been thoroughly explored. The impact of steady flow disturbances on Coriolis flow meters is well-documented, and empirical compensation or correction methods can be implemented accordingly. However, there has been inadequate investigation into the response of Coriolis meters under transient flow conditions and their comparison with steady flow in a wet gas. In this study, a Coriolis device was horizontally installed in a 50 mm pipe diameter. The experimental fluids consisted of air and water, with Lockhart-Martinelli (X_{LM}) values ranging from 0.02 to 0.40. Steady and transient flow conditions at different gas and liquid flow rates were studied. The findings demonstrate the capability of standard deviation (STD) in distinguishing transient flow from steady one. Additionally, a strong correlation was observed between X_{LM} and gas Over-Reading (OR) across various gas flow rates and X_{LM} values. This correlation is particularly evident for $X_{LM} < 0.1$. At extremely low liquid loading ($X_{LM} < 0.05$), the average percentage error remains below 7 % even without the utilization of any correction models. Furthermore, the impact of different sensor installations, which had been largely overlooked in previous studies, was investigated.

Keywords: Coriolis flow meter, Standard Deviation, Sensor Orientation, Two-phase flow, Wet gas

1. Introduction

Wet gas is a gas with a small amount of liquid present. Wet gas widely exists in various processes in the industry such as natural gas production wells, oil–gas exploration and electric power generation. In general, the reliable and accurate metering of wet gas flows allows process products to be accurately estimated, costs to be reduced, and sometimes power efficiency to be increased. However, wet gas flow is an extremely adverse condition that all gas meters struggle with. Obviously, developing an accurate and cost-effective online device for measuring wet gas and liquid flow rates has drawn increasing attention in research [1]. The commonly used wet gas meter is a 'hybrid type wet gas meter', which consists of two or more single-phase meters combined in series. Among hybrid type wet gas meters, it is more likely to apply a void fraction meter to estimate the wetness [2]. While this approach enhances measurement reliability, it also leads to higher costs and increased complexity. From an industrial standpoint, there is a preference for using a single device that can maintain the same level of accuracy and reliability without added expense and complexity. Coriolis devices can meet these requirements if their internal parameters are well-developed in the wet gas conditions. Firstly, Lansangan et al. [3], tried to measure the wetness from the Coriolis data. They presented two approaches for Coriolis mass flow metering in wet gas conditions. The natural extension of the low GVF techniques was to map the observed mass flow and density readings onto estimates of the flow rates of the gas and liquid components. The alternative was to use the Coriolis meter to estimate the degree of gas "wetness" (e.g., the Lockhart-Martinelli number) and to apply a conventional correlation (e.g., Murdock or Chisholm) to a differential pressure flow reading. Tests were carried out at the CEESI gas laboratory in Colorado to develop two-phase models of the meter response to wet gas. A 50 mm flow tube was subject to a range of conditions: Pressure range 115 – 515 psi; Gas flow rates 0.25 – 2.50 million standard cubic feet per day; and X_{LM} range 0.0 – 0.3. Based on their results, 95 % of the test points showed a gas mass flow error of less than 2 %, while 60 % of the test points showed a liquid mass flow error of less than 5 %. However, they didn't use the Coriolis device to directly measure the liquid fraction. Hollingsworth and Morett [4] from EMERSON Co. proposed a new method for wet gas measurement using a Coriolis meter. The performance of Coriolis meters could be greatly improved by using drive power or drive gain (Excitor current divided by the voltage of the sensor signal) to detect when there is a single or two-phase flow in the meter. Drive gain is proportional to the power used to vibrate the meter's flow tubes. In two-phase flow, much of the energy used to drive flow tubes goes into the relative motion between the liquid and gas phases, requiring an increase in drive power to maintain constant tube amplitude. They observed a sharp increase in drive gain when injecting a little water into the gas flow. They didn't go further to provide a model with changes in liquid fraction. In a white paper on Coriolis meters presented by the company E+H, the inhomogeneous medium diagnostic index can be used to describe the relative level of the liquid phase in a wet gas application [5]. However, no experimental data were reported especially in the case of wet gas flow. Meribout et al. [6] presented a Coriolis flow meter combined with an online flow conditioner. They applied an upstream inline flow conditioner which separates liquid (i.e., water in their work) from gas. They presented that drive gain in Coriolis meters is very sensitive to even small amounts of liquid. They showed changes in the drive gain with gas void fraction (GVF) at high and low GVFs. To date, no experimental data has been reported comparing the response of Coriolis meters under steady and transient flow conditions in wet gas flow. Additionally, to the best of the authors' knowledge, no prior investigations have been conducted to examine the response of Coriolis parameters under varying flow patterns or orientations. This paper takes a significant step forward by attempting to understand the Coriolis behaviour in a transient flow condition as well as steady one. Furthermore, the paper explores the influence of different orientation of sensor on the response of Coriolis.

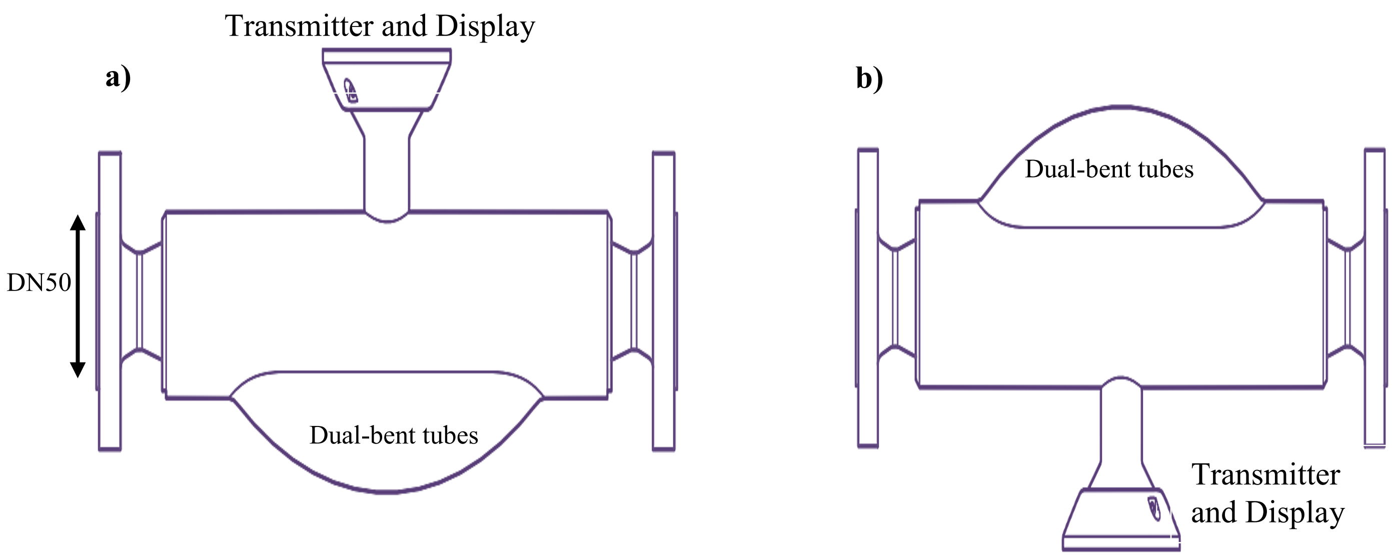

Figure 1: Sketch of Coriolis flow meter: a) belly-down (0 degree) b) belly-up (180 degree).

2. Experimental apparatus

2.1. Coriolis flow meter

Fig. 1 shows the sketch of the Coriolis flow meter used in this study. It's a dual bent-tube Coriolis with a DN50 pipe diameter, equals to 50 mm internal diameter of the connected process pipe. Different orientation as 0 degree (belly-down) and 180 degree (belly-up) were considered in the test. The Coriolis outputs were captured using a Memograph device as an advanced data manager with the capability of logging, signal visualization and analysis. A sampling rate of 1 Hz was applied for all Coriolis meters and the range of the gauge pressure was 0.1 to 0.4 MPa.

2.2. Flow loop

The experiments are carried out on the three-phase flow test rig at Cranfield University which is a fully automated test facility designed to supply a controlled and measured rate of oil, water and air mixture from the flow metering area into the test area and finally into the phase separation area where the oil, water and air are separated (Fig. 2). The 2-inch loop is a 55 m long horizontal pipeline, connecting to a 10.5 m long vertical riser. Wet gas experimental tests are performed using water/air two-phase flow. The flow rates of the air and water are regulated by their respective control valves. The water flow rate is metered by two flow meters: 1-inch Rosemount 8742 Magnetic flow meter (up to 1 kg/s) and ½-inch Coriolis flow meter (up to 1.5 kg/s). Air is generated using three compressors arranged in series to ensure an adequate supply of pressure and flow rates in the pipeline. Before introducing the gas into the main pipeline, a sequence of filters has been installed to provide an extremely dry gas to the system which is important in the case of wet gas flow. The air flow is metered by a bank of three reference meters: Rosemount Mass Probar flow meter in a 1-inch pipe diameter, Ultrasonic and Coriolis flow meters in a 2-inch line. The process involves mixing air with the liquid and then passing it through an extended development region, followed by both horizontal and vertical test sections, respectively. The test facility is controlled by DeltaV, a Fieldbus-based supervisory control and data acquisition (SCADA) software supplied by Emerson Process Management. A variety of auxiliary test equipment is accessible for use with the flow loop, including differential pressure sensors, temperature sensors, and gauge pressure sensors. For capturing flow details within the horizontal test section, an i-SPEED high-speed camera from Olympus equipped with a super-wide-angle lens is employed. The current specifications and operating conditions of the test facility and the major parameters of measurement devices are listed in Table 1.

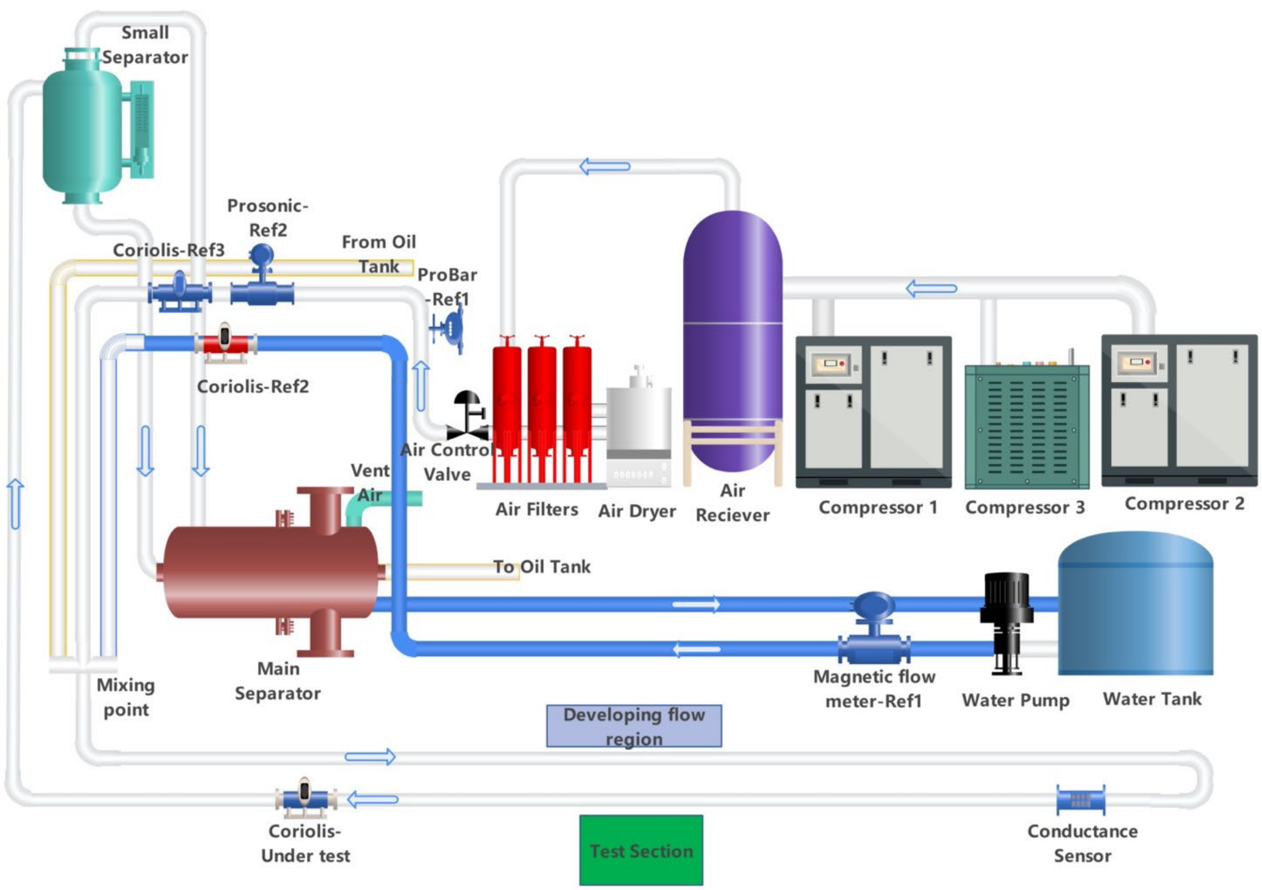

Figure 2: Schematic of 3-phase flow test rig at Cranfield University.

Table 1: Parameters of measurement devices used in the test.

Device	Range	Accuracy	Object
Magnetic flow meter	0 - 1 kg/s	±0.1 %	Water flow rate
Coriolis FM	0 - 1.5 kg/s	±0.1 %	Water flow rate
Mass Probar FM	200 - 1200 kg/hr	±1 %	Gas flow rate
Coriolis FM	200 - 1200 kg/hr	±0.1 %	Gas flow rate
Ultrasonic flow meter	200 - 1000 kg/hr	±0.5 %	Gas flow rate
High-speed camera	200 - 2000 fps	-	Flow regime

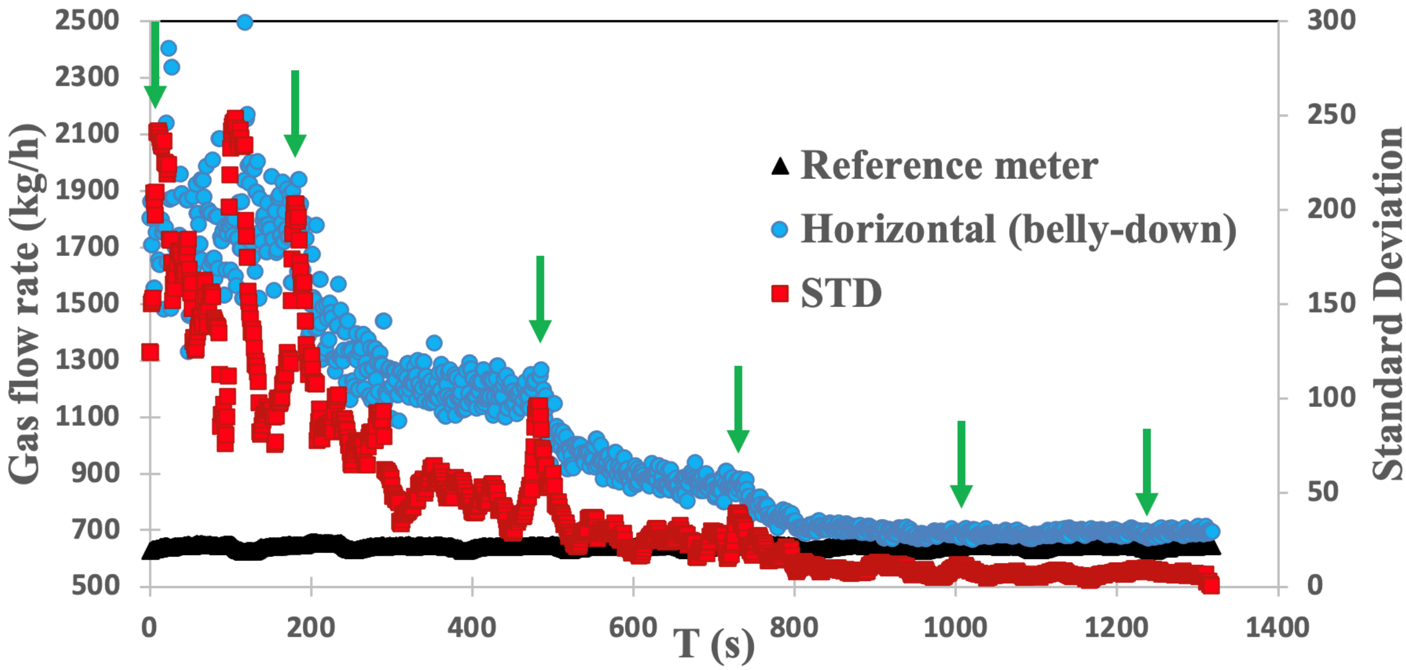

Figure 3: Coriolis output at steady and transient flow conditions at 600 kg/hr gas flow rate and different liquid flow rate from 0.8 kg/s to 0.02 kg/s, and line pressure 3 barg.

3. Results and discussion

3.1. Analysis of Coriolis response in the wet gas flow

Fig. 3 depicts typical results of the Coriolis meter under steady and transient flow conditions. The gas flow rate is held constant at 600 kg/hr while varying the liquid flow rate and maintaining a line pressure of 3 barg. The liquid flow rate varied from 0.8 kg/s to 0.02 kg/s, revealing different flow patterns over time. A green arrow indicates the Coriolis response when the liquid flow rate undergoes changes, signifying a transient flow condition, which could influence the flow pattern. To distinguish between steady and transient conditions, standard deviation (STD) analysis was utilized. It can be calculated as follows:

$$STD = \sum_{i=1}^{n} \sqrt{\frac{(x_i - \mu)^2}{n}} \tag{1}$$

where x_i shows each value from the population, μ is the population mean and n is the size of population. In this article a population mean of twenty consecutive data was considered. Higher STD values imply greater scatter in data points. For instance, at the onset of liquid flow (time zero), a significant scattering of data points, approximately 120-240, is observed, which reduces to 75-180 as the flow stabilizes. This data scattering in the Coriolis response is primarily attributed to the prevalent slug flow pattern in this scenario.

When the liquid flow rate is adjusted to 0.4 kg/hr, a notable spike in STD occurs around 200 s, indicative of transient flow conditions affecting the flow pattern. Similar fluctuations in STD peaks are evident when changing the liquid flow rate at various time points. However, at very low liquid loadings (below 0.05 kg/s), data scattering diminishes substantially, and almost disappearing. This phenomenon is attributed to the extremely low liquid loading and/or the transition in flow pattern from intermittent to stratified conditions. In such instances, even shifts in liquid flow rate between steady and transient states have minimal impact on the Coriolis response.

Another important and useful parameter to compare the effect of flow rate on the response of the Coriolis is gas Over-Reading (OR). The OR is defined as:

$$OR = \frac{\dot{m}_{g,unc.}}{\dot{m}_{g,Ref.}} \tag{2}$$

where $\dot{m}_{g,unc.}$ and $\dot{m}_{g,Ref.}$ present the Coriolis uncorrected mass flow rate and the gas mass flow rate from the reference meter both in $kg.hr^{-1}$, respectively. Fig. 4 illustrates the gas over-reading (OR) results in the horizontal configuration (0 degree or tube down) for the Coriolis meter at transient and steady flow condition of various gas flow rate and different X_{LM} by means of 20 second data averaging. X_{LM} presents the Lockhart-Martinelli parameter, which can be defined as:

$$X_{LM} = \frac{\dot{m}_{l,Ref.}}{\dot{m}_{g,Ref.}} \cdot \sqrt{\frac{\rho_g}{\rho_l}} \tag{3}$$

where $\dot{m}_{l,Ref.}$ presents liquid mass flow rate from the reference meter, ρ_g and ρ_l are gas and liquid density, respectively. Additionally, percentage error (PE) for gas flow rate is defined as:

$$PE(i) = \frac{\dot{m}_{g,unc.}(i) - \dot{m}_{g,Ref.}(i)}{\dot{m}_{g,Ref.}(i)} \times 100\ \% \tag{4}$$

As can be seen in Fig. 4, elevating X_{LM} leads to an increase in the OR across all gas flow rates. Despite a considerable OR, a good linear correlation with the X_{LM} can be observed. A similar trend has been noted by other studies in the wet gas flow (e.g., [4]). Additionally, higher liquid mass flow rates result in fluctuations in the Coriolis response (noted as data scattering), attributed mainly to different flow patterns and higher liquid fraction. Conversely, decreasing the liquid flow rate or wetness reduces the OR as well as scattering in the data points. The results for the Coriolis reveal an excellent overlap between data at different gas flow rates, except for deviations observed at a gas flow rate of 480 kg/hr and $X_{LM} > 0.1$. All the OR data present similar trends and values at $X_{LM} < 0.1$, regardless of different flow patterns.

Fig. 5 illustrates the raw OR data at different flow rate without averaging and in the steady flow condition. As can be seen, even at lower X_{LM} data scattering is obvious specially in the lower gas flow rate. Therefore, using a proper averaging is a good choice to avoid data scattering and prepare the data to develop a correction model. Regarding the error range, for very low liquid loading ($X_{LM} < 0.05$) all error data remains below 10%, with averaging less than 7%. However, as the liquid loading increases ($X_{LM} > 0.05$), the error data gradually rises, making the use of a correction model inevitable.

3.2. Analysis of different orientation of the sensor

Another important factor for Coriolis devices is the sensor orientations or tube angles. In the pure liquid flow, it has been usually suggested to use the belly-down or zero degree to lessen the possible effect of gas bubbles [7]. In the pure gas flow, belly-up or 180 degree is preferable. However, in the wet gas flow, to the best of authors' knowledge no measurement has been taken to provide the optimum angle. To this end, a set of experiments were carried out at different tube angles: 0 degree; and 180-degree as can be seen in Fig. 1. The results are presented in Fig. 6.

In the 180-degree orientation, there is a notable linear correlation with X_{LM}, but disparities appear at $X_{LM} > 0.2$ for different flow rates. Also, a higher over-reading (OR) can be seen compared to other orientations. Additionally, significant scattering in the response is evident at very low X_{LM}.

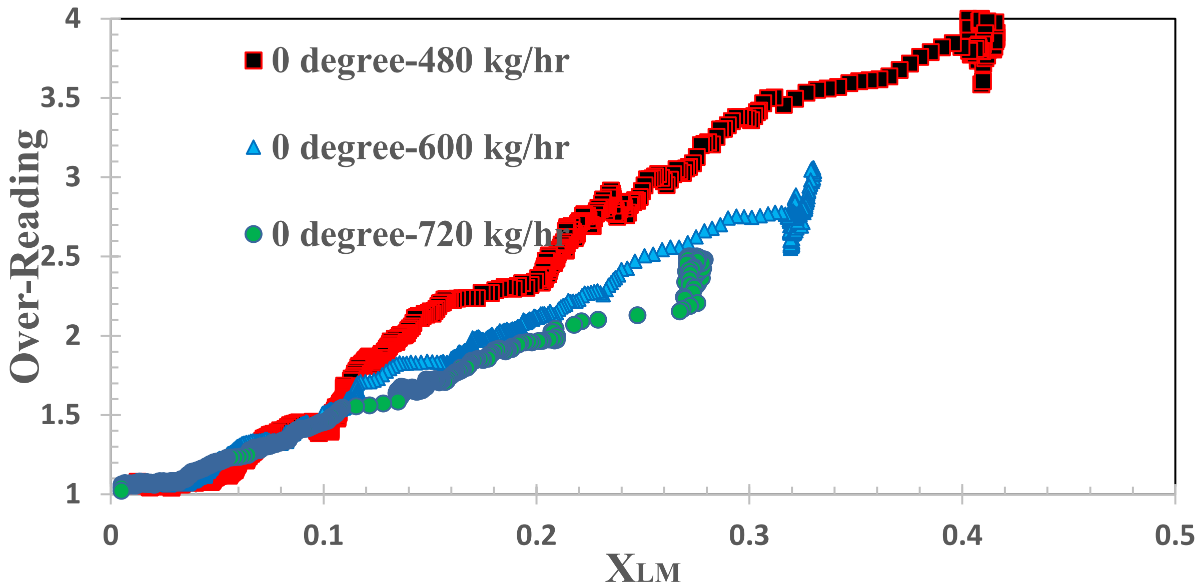

Figure 4: Gas over-reading of Coriolis meter in steady and transient flow conditions at different gas flow rates in the horizontal position (0 degree) and line pressure 3 barg.

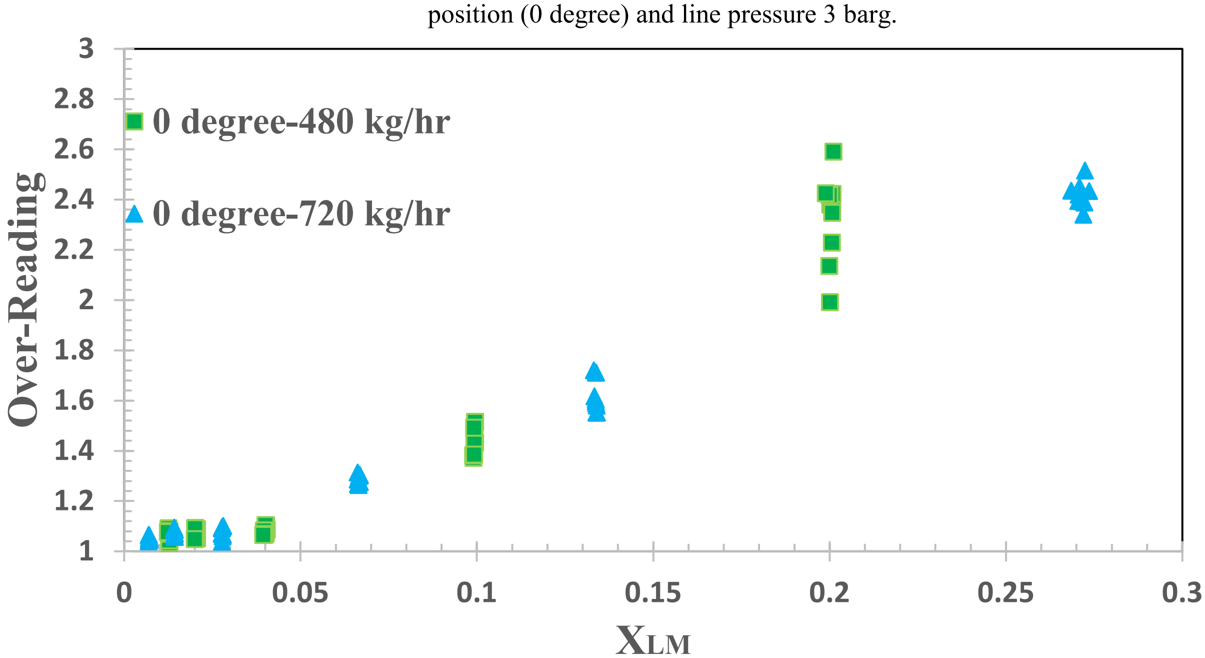

Figure 5: Gas over-reading of Coriolis meter in the steady condition at different gas flow rates in 0 degree and line pressure 3 barg.

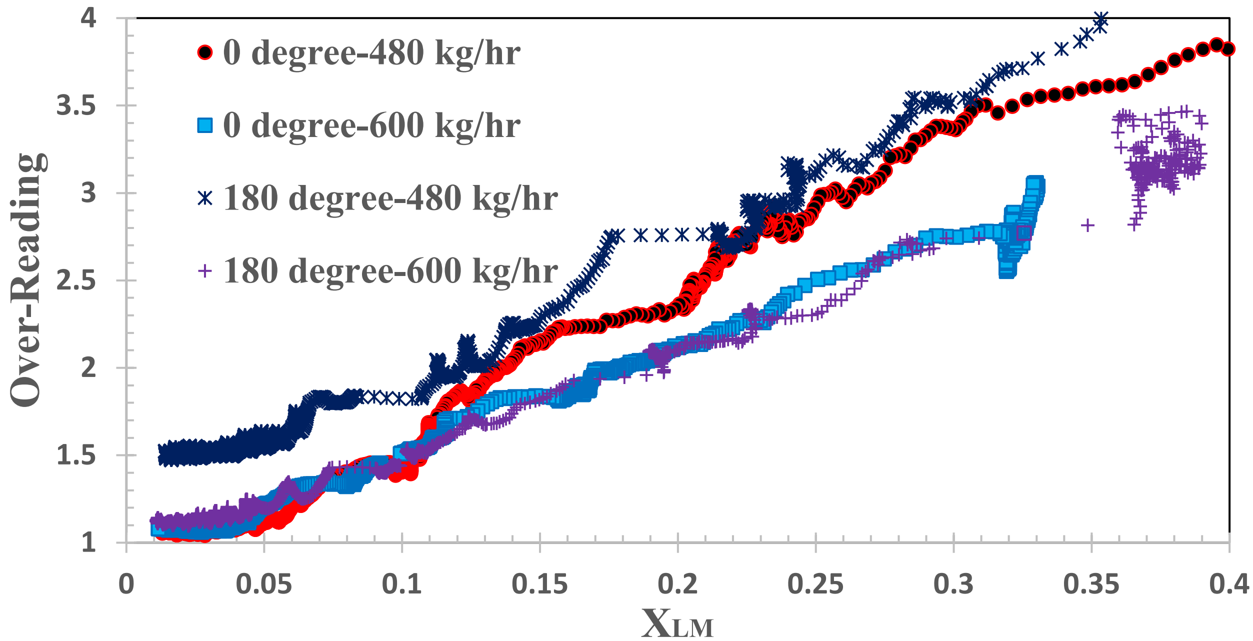

Figure 6: Gas over-reading of Coriolis at different angles and gas flow rates in the horizontal position and line pressure 3 barg.

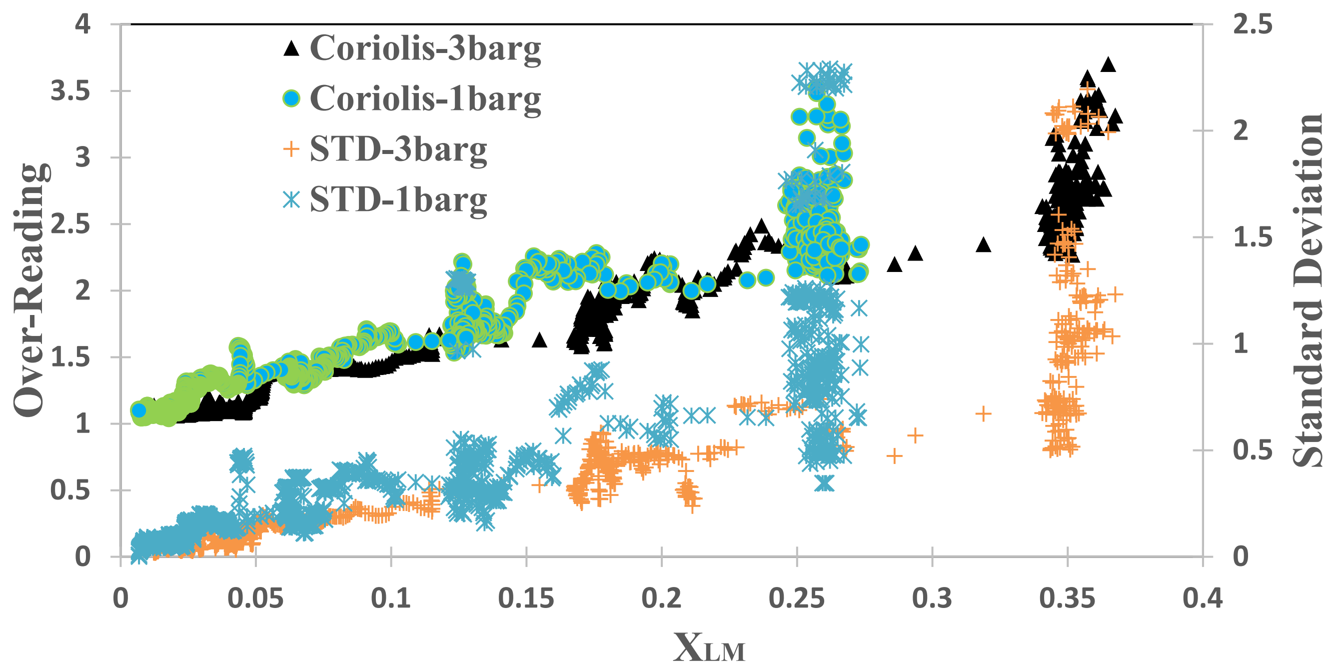

Figure 7: Pressure effect on the Coriolis response at 600 kg/hr gas flow rate.

3.3. Analysis of pressure effect on the response

Fig. 7 shows the response of the Coriolis meter at different pressures. The trends and values remain largely consistent, except for the variance in data distribution, as indicated by the standard deviation (STD) values. More data scattering is evident at lower pressures compared to higher pressures. Explaining this trend is challenging, but it could be linked to smaller density differences between liquid and gas flow at higher pressures. Further exploration is needed, particularly focusing on higher pressure ranges.

4. Conclusion

This study explored the performance of a Coriolis meter under varying wet gas flow conditions, including steady-state and transient flow. Additionally, it investigated several parameters such as wetness (X_{LM}), sensor installation, and pressure on the response of Coriolis in a wet gas flow. Transient flow conditions exhibited a peak in STD data, serving as a distinguishing factor from steady flow conditions. However, minimal changes were observed in STD data under very low liquid loading ($X_{LM} < 0.05$) with an average error less than 7 %. However, as the liquid loading increases ($X_{LM} > 0.05$), the error data gradually rises, indicating the necessity of employing a correction model. The results demonstrated a strong correlation between gas Over-Reading and X_{LM} across different gas flow rates, particularly at $X_{LM} < 0.1$, regardless of flow patterns. Furthermore, a comparison of sensor orientation in the horizontal position favoured the 0-degree angle over 180 degrees. This orientation shows a more linear OR curve with overlapping results at varying gas flow rates. Future investigations could involve exploring different angles in the horizontal position and comparing them with the vertical configuration.

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