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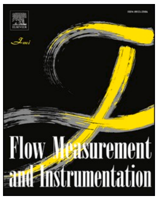

Devices and methods for wet gas flow metering: A comprehensive review

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ABSTRACT

Wet gas is commonly encountered in various industries, including energy, chemical, and electric power sectors. For example, natural gas extracted from production often contains small amounts of liquid, such as water and hydrocarbon condensates, which classifies it as wet gas. The presence of liquid within the gas poses challenges for accurate flow measurement. To improve the performances of wet gas flow metering methods, significant research and development efforts have been invested into the wet gas flow metering technologies due to their vital importance in the production, transfer, and trade benefits.

This paper presents a comprehensive overview of the recent development of wet gas flow metering. Firstly, a comprehensive discussion of the Lockhart-Martinelli parameter (X_{lm}) and its relation to the gas void fraction (α_g) is presented, which was mostly overlooked in previous wet gas research work. The occurrence of various flow patterns in wet gas conditions at different orientations (horizontal and vertical) was explored. Following an investigation of pressure impact on the wet gas flow patterns and development of the wet gas regions, a different test matrix for further research work was suggested. After a novel classification of wet gas measurement methods, the paper offers a detailed comparison of differential pressure (DP) meters including Venturi, Cone meter, and orifice meters, by considering both liquid and gas flow rate measurements. Secondly, the paper discusses and compares vortex flow meters, Coriolis and ultrasonic meters in comparison to DP meters. Notable phase fraction meters are also examined and compared to one another. Thirdly, the paper reviewed the concept of existing and potential hybrid wet gas meters, conducting a detailed discussion and comparison with commercial solutions by evaluating their ranges and accuracies. This assessment provides valuable insights into the capabilities of these hybrid meters, highlighting their potential to enhance the measurement of wet gas flow rates.

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. For example, in the oil and gas industries, the gas flow rate and liquid flow rate of the wet gas are important parameters reflecting the output of a single well and they are also of great significance for accurately measuring the amount of liquid in gas reservoirs, reasonably prorating the production, and efficiently designing the techniques for increasing production.

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. Nevertheless, wet gas flow is an adverse condition that requires both the technology development and good engineering practice to achieve its accurate measurements. To improve the performance of the metering system and technology a suitable methodology has to be applied depending on the instrument and the type of flow meter available or installed.

Developing an accurate and cost-effective online device for measuring wet gas and liquid flow rates has drawn increasing attention in research [1]. Commercially, 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. The majority of these wet gas meters are made up of differential pressure meters (e.g., Venturi, Cone meter, and orifice) and other flowmeters and sensors, such as velocity flowmeters, volumetric flowmeters, mass flowmeters, γ-ray sensors, microwave sensor, and infrared sensor [2,3]. These existing measurement devices can predict the wet gas accurately, but they are practically limited by their innate disadvantages including the complex structure and large

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size. In addition, some of them contain radiation-emitting devices which may make their operation rather difficult. Most importantly, owing to their high price, they are not applicable in some wet gas conditions such as natural gas wells with low production [4].

Due to the importance of the topic, there have been a number of published review papers and work on wet gas flow metering, for example, a review on using single phase flow meters for wet gas measurement by Munari and Pinelli was presented in Ref. [5]; a comprehensive work on Venturi meter used for wet gas metering purposes by Steven was reported in Ref. [6]; and Zhang and Wang reviewed the shale gas metering [7]. However, this review intends to examine the research and development of water gas metering in a more comprehensive manner. It covers commercially available wet gas measurement techniques and even their combination methods; it also includes those on the research development stage. The potential and limitations of each of the meters, and the published research results will also be highlighted.

This review will be structured as the following sections.

- Section 2: The fundamentals of wet gas flow and its different flow patterns will be explained. Besides, the definition of wet gas flow based on the Lockhart-Martinelli parameter and the significance of gas void fraction in wet gas conditions are deeply discussed, which has largely been overlooked in the previous literature. Also, the effect of pressure on the wet gas flow patterns is described. Additionally, a detailed description of wet gas regions has been mentioned which might be very valuable for future research.
- Section 3: Different methods for wet gas meters are classified based on flow rate metering and phase fraction measurement. In this section, a comprehensive review of each method, as well as its pros and cons, will be elaborated.
- Section 4: A combination of different technologies and their performance in wet gas will be discussed.
- Section 5: Available wet gas flow meters in the market will be introduced in this section.
- Section 6: Provides some information about the way ahead of wet gas flow measurements. Finally, a brief conclusion has been mentioned.

2. Fundamentals of wet gas

2.1. Lockhart-Martinelli parameter (X_{LM}) for wet gas flow

Wet gas is a term with various interpretations in literature, lacking a single definitive definition. According to ISO/TR 11583 [8], if the gas volumetric fraction (GVF) of a gas–liquid two-phase flow is larger than 95 %, it is considered as a wet gas. In the oil and gas industry, the tendency is to use the term wet gas for flows that have a GVF, higher than 90 % [9,10]. However, a crucial aspect of wet gas is the actual liquid fraction present in the gas flow. X_{LM}, is commonly used to assess the relative amount of liquid in a two-phase wet gas flow. This parameter, developed by Lockhart and Martinelli in 1949 [11] and later modified by Chisolm in 1967 and 1977 [12,13], enables the determination of the wetness of the mixture based on the gas and liquid flow rates and their densities, independent of pipe roughness, friction factor, or meter type. It is defined as follows:

$$X_{LM}=\frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_l}} \tag{1}$$

Hall [14] reported that a wet gas flow can be defined as any gas and liquid flow with a condition of $X_{LM} < 0.3$. This definition is more accepted and generally supported by different organizations: the American Society of Mechanical Engineering (ASME), the American Petroleum Institute (API) [5], and ISO/TR 12748:2015 [15].

While X_{LM} is an imperative parameter in wet gas system, the relation between this parameter, gas volume fraction (GVF) and gas void fraction (α_g) needs further attention. Gas void fraction can be defined as the ratio of gas cross-sectional area to total pipe cross sectional area:

$$\alpha_g=\frac{A_g}{A} \tag{2}$$

And GVF is the ratio of gas to total fluid volume flow rate at actual flow conditions as follows:

$$GVF=\frac{Q_g}{Q_g+Q_l}=\frac{1}{1+\left[\frac{Q_l}{Q_g}\right]}=\frac{1}{1+\left[\frac{\dot{m}_l}{\dot{m}_g}\cdot\frac{\rho_g}{\rho_l}\right]}=\frac{\sqrt{\frac{\rho_l}{\rho_g}}}{X_{LM}+\sqrt{\frac{\rho_l}{\rho_g}}} \tag{3}$$

The Gas Volume Fraction (GVF) is a dynamic measurement of volume flow rates that inherently considers the slip between liquid and gas phases. In contrast, gas void fraction is a static measurement taken at a specific moment in time and does not account for the slip between the phases [15]. Just in the homogenous model, where no-slip between phases is assumed, the value of GVF and α_g become identical. The homogenous flow model is limited to bubbly flow and dispersed or mist flow where both phases travel at the same velocity [16]. Therefore, by introducing a difference in both phase velocities, a correlation between gas void fraction and X_{LM} can be achieved:

$$\alpha_g=\frac{\sqrt{\frac{\rho_l}{\rho_g}}}{SX_{LM}+\sqrt{\frac{\rho_l}{\rho_g}}} \tag{4}$$

Where $S=\frac{U_g}{U_l}$, is the slip ratio between gas and liquid local velocities. Because obtaining the slip velocity is not straightforward, therefore some literature offered empirical correlations. One of these models proposed by MacFarlane [17] as follows:

$$\alpha_g=1-\left[1+\frac{21}{X_{LM}}+\frac{1}{{X_{LM}}^2}\right]^{-0.5} \tag{5}$$

Abdul-Majeed [18] presented a modified Taitel and Dukler correlation for estimating the liquid hold-up in a horizontal oil-gas two-phase flow (Eq. (5)). For turbulent flow, it can be expressed as:

$$\alpha_l=\exp\left(-0.930+0.528R-0.0922R^2+0.0009R^4\right),R=Ln(X_{LM}) \tag{6}$$

where α_l (=1-α_g) is the ratio of liquid cross –sectional area to total pipe cross-sectional area or the liquid hold up. Also, Awad and Muzychka [19] suggested a model with two bounds for α_g as a function of X_{LM}. They mentioned that the model can be used for a wide range of pressures, pipe diameters and mass flow rates for different two-phase fluids. For the lower bound:

$$\alpha_g=\frac{1}{1+{X_{LM}}^{\frac{16}{19}}} \tag{7}$$

And for the upper bound:

$$\alpha_g=\frac{1}{1+0.28{X_{LM}}^{0.71}} \tag{8}$$

Although the void fraction in a two-phase flow is influenced by various parameters, such as fluid and pipe properties, pressure and temperature conditions, and flow patterns, comparing these models with actual data can provide valuable insights. Fig. 1 depicts a comparison of these models with two sets of experimental data [18,20]. It is evident that the assumption of homogeneous flow significantly deviates from reality. Macfarlane, Abdul-Majeed, and Awad-Upper bound models exhibit favourable results in predicting α_l when $X_{LM}<0.1$, particularly when compared with Abdul-Majeed's data. However, concerning $X_{LM}>0.1$, only the Awad-Lower bound model manages to predict the trend. Several noteworthy points should be highlighted here. The assumption of equality of GVF and α_g is an approach that may not be valid in many cases. By relying on this notion and disregarding the

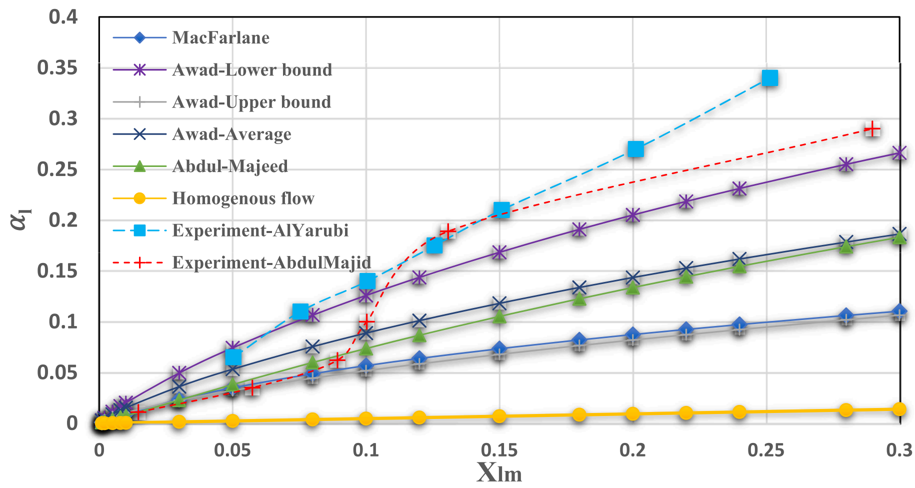


Fig. 1. Comparison of different models with experimental data (dashed blue and red lines) to estimate α_l from X_{LM}.

measurement of true α_l, one might make the additional assumption that α_l is limited to a maximum of 5 % or 10 % at $X_{LM}<0.3$, which is incorrect. As indicated by experimental data, α_l can surpass 30 % even at $X_{LM} = 0.3$. Consequently, relying solely on X_{LM} or GVF to describe wetness can lead to a misunderstanding of the true wet gas flow scenario, impacting the accuracy of gas and liquid flow rate assessments. As of the authors' knowledge, no model has been developed to effectively correlate X_{LM} and α_l or α_g, under wet gas conditions.

2.2. Flow pattern in wet gas conditions

A crucial aspect when measuring wet gas flows is the distribution of the liquid and gas components within a pipe, as this distribution can affect the accuracy of the measuring device [21]. This distribution is usually called "flow patterns" or "flow regimes". The various types (Horizontal and vertical-upward) of flow patterns are shown in Figs. 2 and 3. For the gas-liquid two-phase flow in a horizontal pipe, the gas phase will gather to the top of the pipeline due to gravity and buoyancy. In all horizontal wet gas flow regimes, the gas velocity exceeds the liquid velocity, indicating a slip between the phases [15]. The horizontal flow pattern can be divided into bubbly flow, intermittent flow including slug flow and plug flow, stratified flow, and annular flow. For gas-liquid two-phase flow in a vertical pipe, the distribution of two-phase flow is generally axis-symmetrical, including bubbly flow, dispersed-bubbly flow, slug flow, churn flow, and annular flow. The generation of one flow pattern rather than another depends on the flow conditions (gas and liquid flow rates, pressure, temperature, pipe diameter, properties of the flow components etc.). Therefore, it is difficult to predict the type of flow pattern. Although there is less information on flow regimes in wet gas flow stratified wavy, roll-wave and annular flow and less frequent churn, stratified and slug flow can be observed in a wet gas condition. It's worth noting that roll-wave flow actually represents a transitional region between stratified wavy and annular flow patterns. It is obvious that stratified or wavy flow can be witnessed just in a horizontal pipe and churn flow in the vertical one. The flow regime maps of Figs. 2 and 3 show the wet gas regions for air/water two-phase flow in a 2-inch pipe diameter at different pressures and X_{LMs} for horizontal and vertical orientations, respectively. It can be observed that pressure is a significant factor in estimating flow patterns, especially in horizontal tubes. At pressures lower than 4 bar, and by considering the maximum X_{LM} of 0.3, slug flow is not apparent. However, as pressure increases and gas velocity decreases, slug patterns become distinguishable. For instance, at 80 bar and X_{LM} of 0.3 in a horizontal pipe, slug flow is more likely to occur rather than the annular one. These observations can be attributed to the increased similarity in density between the two phases as the pressure rises. Nevertheless, the most common flow pattern in wet gas conditions remains annular flow in both vertical and horizontal orientations, followed by wavy and churn flow. While all the curves exhibit similar trends, there are variations in slope, depending on parameters such as X_{LM} and density ratio. Additionally, highlighting this

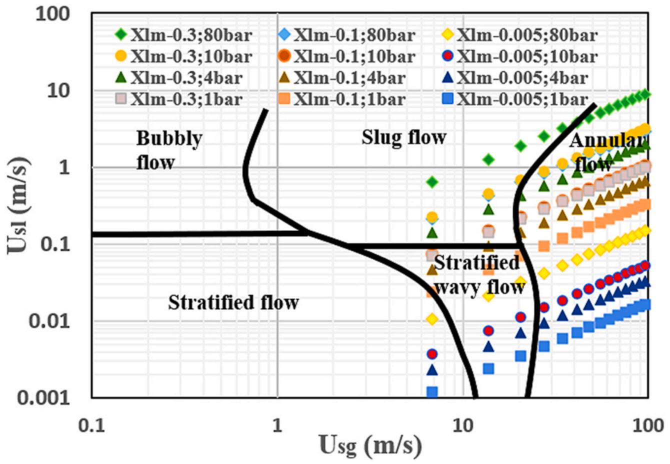


Fig. 2. Wet gas region of air-water two-phase flow in a horizontal pipe at different pressures based on Mandhane flow regime map [23].

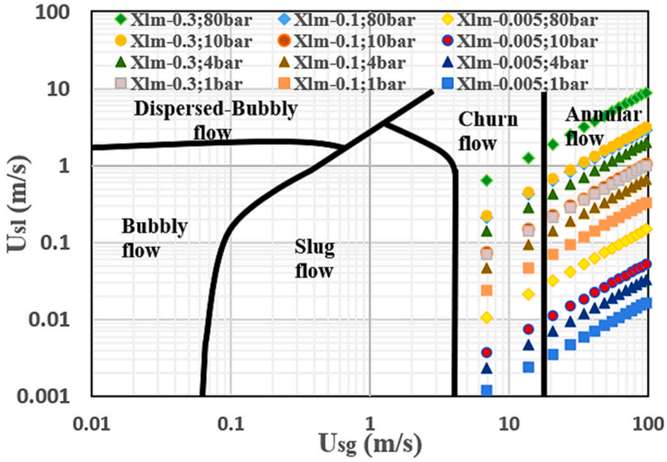


Fig. 3. Wet gas region of air-water two-phase flow in a vertical upward flow at different pressures by considering flow regime map presented in Ref. [24].

trend can help in establishing a better correlation between various parameters in the wet gas flow. The same approach can be applied to the study of oil and gas two-phase flow in the wet gas conditions. The understanding of inclined pipe flow regimes is not as well-documented compared to that of horizontal and vertical flow regimes [22]. It is acknowledged that even a slight deviation, whether positive or negative, from the horizontal orientation can have a significant impact on the flow regime [15].

3. Classification of wet gas metering techniques

Currently, there are additional pressures for accurate wet gas metering, particularly in allocation, monitoring of production and the moves towards fiscal metering for newly developed marginal and large gas fields [25]. A few wet gas metering technologies have been developed and some are currently available commercially, but most metering technologies are still being tested, analyzed, and validated. Fig. 4 shows the classification adopted in this paper for wet gas scenario. This classification is based on the methods or devices presently accessible for wet gas metering (e.g., Table 4). This report aims to encompass these methods, with the exclusion of radioactive techniques like gamma ray measurements. As it is shown in Fig. 4, wet gas devices consist of two main parts: flow rate measurement devices and phase fraction measurement devices. Flow rate meters are extensively employed for measuring the flow rate of the gas phase or both phases, whereas phase fraction meters are specifically designed for measuring the fraction of each phase. Flow rate measurement devices can further be divided into three distinct types: differential pressure (DP) based methods, flow-induced dynamics based methods, and fluid velocity methods.

3.1. Flow rate metering methods

3.1.1. Differential pressure (DP) based methods

The differential pressure (DP) meters are widely used in the oil and gas industry due to their robust performance and low-cost expenditure, such as the Venturi meter, the orifice plate meter, and the Cone meter. Based on Bernoulli formula, mass flow rate of single-phase fluid (e.g. pure gas) is proportional to the square root of differential pressure across a DP meter as per the following formula [26]:

$$m_g = \frac{C\varepsilon A_T}{\sqrt{1-\beta^4}} \cdot \sqrt{2\rho_g \Delta P_g} \tag{9}$$

Where C is the discharge coefficient; A_T is the area of the throat; ε is the expansibility factor; ρ_g is gas density; β is the diameter ratio (e.g., throat diameter to pipe diameter) and ΔP_g presents differential pressure between low and high pressure regions. The performance of these flow meters, along with their associated uncertainties, have been discussed in ISO 5167:2022 [27–29]. When a DP meter is used to measure the wet gas flow rate, it usually overestimates the actual gas flow rate, which is referred to as an "over-reading (OR)". A generic DP device presents different prediction errors depending on many factors: pipe geometry, gas velocity, flow pattern, pressure and temperature, liquid density, liquid viscosity, and gas-liquid interfacial tension. Based on these factors, over the years several correlations have been developed to allow the correction of the measured mass flow rate error due to the presence of liquid [30,31]. The main important models are the Murdock and Chisholm equation, for the orifice plate, and the de Leeuw equation for Venturi [5]. All the correlations focus on the continuous phase, and the liquid flow rate or the liquid fraction needs to be known prior to the measurement. However, such parameters are difficult to obtain in practical applications. Additionally, each correlation can have a specific and limited range of application (in terms of geometry, pressure, temperature, X_{LM}, etc.). Therefore, if used outside this range, large measurement errors occur, as shown in the work of Stewart [32] and Reader-Harris and Graham [33]. This paper will not elaborate on those OR models, as they can be found elsewhere (e.g. Ref. [34]).

A significant parameter for DP meters to tackle the OR issue is the Pressure Loss Ratio (PLR) which presents the ratio of the permanent pressure loss and traditional DP (ΔP_g). In 1997 de Leeuw [35] discussed reading a Venturi meter's permanent pressure loss in addition to the traditional DP, to calculate the two wet gas flow unknowns, i.e. gas and liquid flowrates. de Leeuw demonstrated that PLR was related to the liquid loading, i.e. $X_{LM} = f(PLR)$. Presently, the industry recognizes that this relationship holds true for various DP meter designs, including Venturi, Cone meter, and orifice meter [6]. Moreover, ISO/TR 11583 [8] provides algorithms for calculating X_{LM} as a function of PLR, DR, and β for select Venturi and orifice meters. Besides, some commercial wet gas meters are employing this parameter to determine the liquid fraction that will be discussed in section 5.

3.1.1.1. Orifice plate. Orifice plates have been historically utilized for a wide range of applications including wet gas [8,36]. They are not typically the first choice for installation in wet gas conditions, but they can effectively handle wet gas flow when it does pass through them [37]. The main issue when using orifice plates in the wet gas flow is the potential of a liquid slug causing them to bend. This risk can be mitigated by manufacturing these plates with maximum allowable thickness as recommended by ISO 5167–2:2022 [27]. Furthermore, orifice plates are less prone to bending if they are secured between flanges rather than within fittings [37]. The orifice meter theory is given by Bernoulli's Equation (Eq. (8)). The name essentially describes the orifice plate itself as a plate with a hole machined into it, which is inserted into a pipe to measure the flowing fluid. As flow passes through, the constriction created by the orifice produces a pressure difference from the upstream to the downstream of the orifice plate (Fig. 5). One of the common types

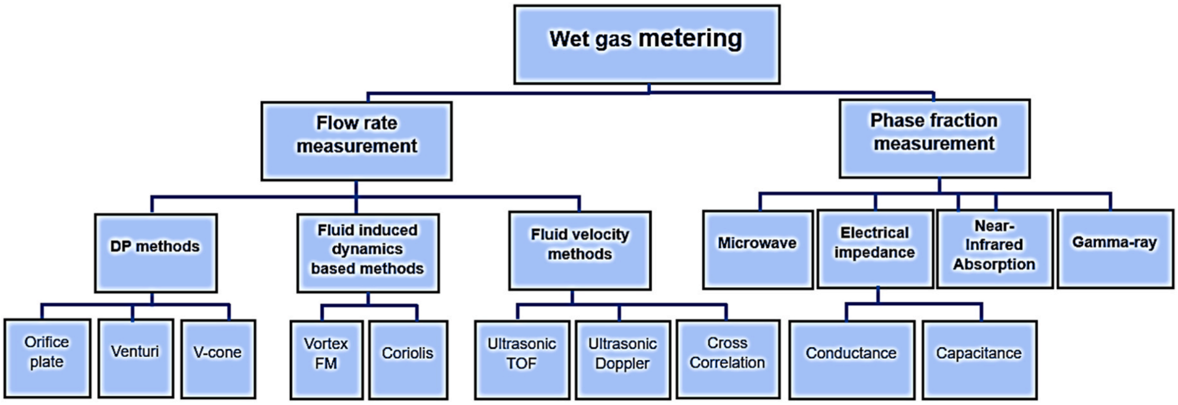


Fig. 4. Classification of most applicable methods for wet gas measurement.

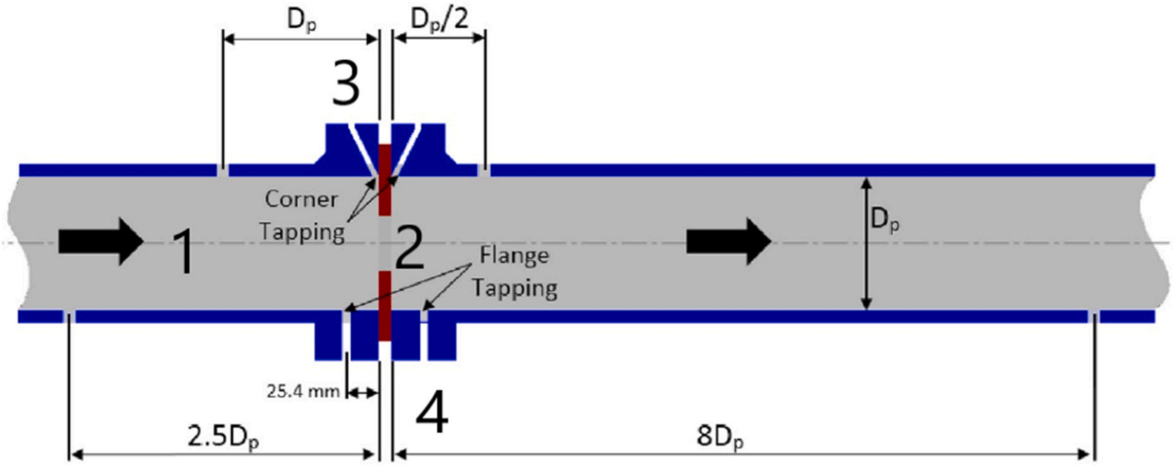


Fig. 5. Fluid flow through a measurement orifice: 1 -flow direction, 2 -orifice, 3 -corner tapping, 4 -flange tapping [39].

of orifice meters uses square-edged concentric plates with flange taps for measuring points. The AGA Report No.3 [38] and ISO 5167–2:2022 [27], provide the specification for this type of orifice meter set-up with the most readily available flow coefficients from extensive testing and studies. For the orifice meter to measure within the specified uncertainty, the measuring fluids must be under steady-state mass flow conditions and considered to be clean, single-phase, homogeneous, and Newtonian with pipe Reynolds numbers of 4000 or greater [38].

Ting investigated the effect of orifice orientation in wet gas flow using a typical orifice plate. Experiments were carried out at the Chevron Petroleum Technology Company's Air How Facility in La Habra, California [40]. Testing involved two-inch orifice meters with three different orifice/pipe diameter ratios (beta ratios). The study's findings reveal that liquid entrainment in orifice meters leads to lower gas flow rate measurement, up to −2 % at vertical upward flow position. To mitigate metering inaccuracies, they suggested to install an orifice meter horizontally, preferably with a beta ratio that falls within the mid-range.

Recently there have been some developments in orifice's shape to reduce the pressure loss, entertainment problems, and increase accuracy in wet gas flow such as the slotted orifice plate by Tomaszewska-Wach [31] and multi-orifice by Ma et al. [41] (See Fig. 6). However, first time, Morrison et al. introduced slotted orifice and compared it to standard one [42]. After that, there have been some modifications to this type of orifice. For example [43],applied double orifice plate accompanied by a neural network for wet gas flow measurement. Four measured DP signals, after digital filtering, were used as input to a back propagation neural network. They used a three-layer BP network. The results show that at a 90 % confidence level the relative error was within ±6 % for Q_g and ±9 % for Q_l in the GVF range of 90–100 % and gas flow rate of 100–1000 $m^3 h^{-1}$. A wet gas meter based on a slotted orifice and Swirlmeter combination in series was designed and investigated [44]. The slotted orifice was put forward. Their sketch of swirlmeter consisted of: (1) fixed swirl blades; (2) a throat and an expansion cone in a spool piece ('Venturi' like tube); (3) swirl blades; and (4) two piezoelectric sensors. A turbine-shaped inlet section forces the axial flow entering the flow meter into a rotational movement. A vortex core forms in the centre of the primary rotation. Then the flow is contracted and expanded in a Venturi-like passage, and the backflow forces the vortex into a secondary spiral rotation which is also known as precession motion [28]. The frequency of this secondary rotation is linearly proportional to the gas flow rate m_g over a wide Reynolds Number range. Their results show that the proposed approach predicts the gas mass flowrate relative errors within 76 % from 89.2 % of tested samples.

Bai and Zheng [45] proposed a new parameter termed the two-phase mass flow coefficient (K) and whereby new wet gas correlations were developed. Their Experiments with an orifice plate, at a pressure range of 0.7–1 MPa and gas flow rate of 200–400 kg/h, and liquid flow rate 0–350 kg/h, indicated that, compared to OR, K increases with better linearity as the Lockhart-Martinelli parameter (X_{LM}) increases within the whole operating range and is more sensitive to the change of X_{LM}. The relative error of gas mass flow rate predicted by the new correlation was within ±3.0 % at the confidence level of 98.6 %, superior to the existing correlations based on OR. Liu et al. [9] presented the pressure drop characteristics of a wet gas flowing through a sharp–edged orifice plate in the transition region. The predictive accuracy of the existing pressure drop models was evaluated using experimental data. The findings indicate that homogeneous flow models tend to overestimate the pressure drop, while models based on the separated flow approach frequently exhibit underestimations. Additionally, the pressure drop models designed for wet gas conditions struggle to provide accurate predictions within this range, often showing errors exceeding 20 %. To

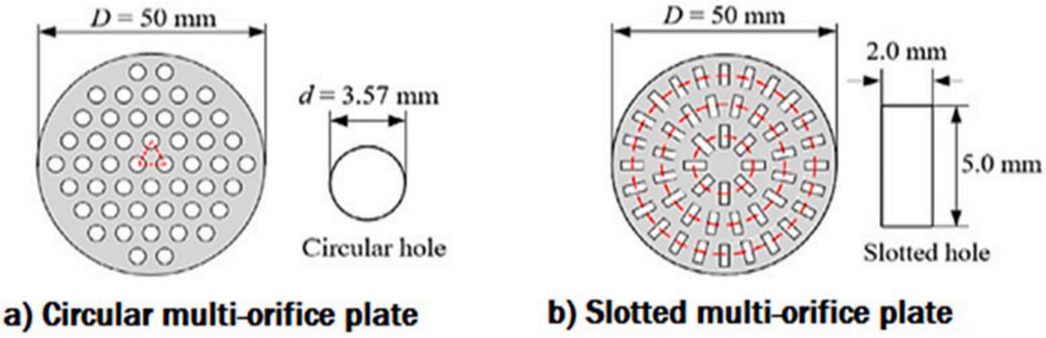


Fig. 6. Structural parameters of the multi-orifice plates [41].

address this limitation, two new correlations were introduced in this study by modifying the Chisholm and Murdock models with accuracies of approximately 6 % and 8 % respectively.

As was mentioned earlier, Ma et al. [41] investigated the pressure drop characteristics of wet gas flowing horizontally across a multi-orifice plate at gas flow rate 40–120 $m^3 h^{-1}$ and GVF 99.8–100, with circular holes and slotted holes. The flow visualization experiment showed that, when the upstream of the multi-orifice plate exhibited stratified flow, the downstream could exhibit stratified flow or annular-mist flow. When the upstream was in the flow pattern transition region, the down-stream mainly behaved as an annular-mist flow. This indicated that the throttling of the multi-orifice plate has an atomization effect, so that the flow pattern behind the multi-orifice plate was mostly a fully dispersed mist flow. As the liquid content in the wet gas increased, the atomization effect became more obvious. Among the proposed correlations, that of the modified Murdock model exhibited optimal prediction accuracies of 15 % and 6 % for the flow pattern transition region and stratified flow region, respectively. Also, at the same porosity, there is no significant difference between circular and slotted multi-orifice plates in pressure drop characteristics. However, the accuracy of the circular multi-orifice plate was slightly better in the transition region. Tomaszewska-Wach and Rzasa [31] carried out experiments on a standard orifice and three types of slotted orifices with various slot arrangements and geometries. The experiments were conducted for three constant mass air flow rates equal to 0.06, 0.078 and 0.086 kg/s. It was found that the slotted orifice generates smaller differential pressure values compared to the standard orifice. The same results were reported by Durdevic et al. [46], when comparing single-hole and multi-hole orifice in a gas single-phase flow. They presented an OR model and compared with the previous model which showed better accuracy of their model. The root mean square relative error was found to be 0.9–1.8 %. Despite those corrections in orifice configuration, the problem of atomization and changing the downstream flow pattern still remains [41].

Recently, Ma et al. [47], investigated the flow pattern difference in the upstream and downstream of a single orifice plate. They performed experiments in a 50 mm pipe with air/water wet gas flow for the intermittent and stratified flow which corresponds to a low $\mathrm{Fr_g}$ number. The gas and liquid Froude numbers can be defined as follows:

$$Fr_g = \frac{U_{sg}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l-\rho_g}} = \frac{\dot{m}_g}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_g(\rho_l-\rho_g)}} \tag{10}$$

$$Fr_l = \frac{U_{sl}}{\sqrt{gD}}\sqrt{\frac{\rho_g}{\rho_l-\rho_g}} = \frac{\dot{m}_l}{A\sqrt{gD}}\sqrt{\frac{1}{\rho_l(\rho_l-\rho_g)}} \tag{11}$$

Where U_{sg} and U_{sl} are gas and liquid superficial velocities, and $\dot{m}_g$ and $\dot{m}_l$ are gas and liquid mass flow rates, respectively. D shows the pipe diameter, A is the cross-sectional area and g is the acceleration due to gravity. They found that in the stratified flow, the downstream of the orifice plate can be divided into a stratified flow and annular-mist flow depending on the $\mathrm{Fr_g}$ number. Also, the results confirmed that there is annular-mist flow downstream of the single orifice plate when the upstream is in the transition region. Also, it was shown that both $\mathrm{Fr_g}$ and $\mathrm{Fr_l}$ are important parameters that affect the wet gas pressure drop of single orifice plates; and the influence of $\mathrm{Fr_g}$ and $\mathrm{Fr_l}$ on the pressure drop characteristics are obvious in the transition region, while are slight in the stratified region. Finally, they used $\mathrm{Fr_g}$ and $\mathrm{Fr_l}$ data to evaluate the available pressure models. Among all those modified models, Chisholm shows the best accuracy while there are still great deviations in the transient region. It seems that more work needs to be done in the case of transient flow patterns, especially for the high $\mathrm{Fr_g}$ numbers.

3.1.1.2. Venturi meter. As a DP flow meter, the Venturi meter distinguishes itself in metering the dry gas flow with high accuracy, good rangeability, low energy dissipation, and robust to upstream disturbances [28], it also behaves well in the wet gas flow rate measurement [48]. Venturi is a throat shape device which the fluid is passing through. The Venturi tube cross-section is shown in Fig. 7. If the fluid passes through the Venturi, it creates a pressure drop between the inlet and throat section of Venturi. Most of the wet gas flow rate measurement prototypes and the marketed gas–liquid flow rate meters are based on the Venturi meter [49]. The reasons for selecting these devices include their physical robustness, which enables them to withstand erosion and the effects of high-velocity liquid slugs, as well as the familiarity with their application [37]. For example, Xu et al. [50] proposed a double DP wet gas flow rate metering device by using the Venturi meter and the Cone meter in series. Agar and Farchy [51] suggested a wet gas measurement method based on the Venturi meter and the sonar sensor. The Dualstream II wet gas metering systems produced by the Solartron ISA [51] applied the double Venturi meters. The TEA Sistemi S.R.L. (2001) and the Roxar Flow Measurement (2002) developed wet gas meters by using the Venturi tube [49]. Usually, for wet gas flow metering, Venturi is preferred, due to the following reasons. Firstly, permanent pressure drop which is created in the pipeline as a result of having a Venturi is less than other flow measuring methods using differential pressure measurement. Secondly, it creates less restriction for fluid passage compared to other differential pressure methods for flow measurement (e.g. orifice). Allowing for measurement over a wider range of flow rates and process conditions, Venturi is able to withstand higher pressure drop compared to other differential pressure methods (e.g. orifice).

Lupeau et al. [52] investigated film and liquid droplet interactions in a Venturi tube. The Venturi was placed in vertical orientation and $\mathrm{X_{LM}}$ was less than 0.02. The flow was divided into two regions: the convergent section and the throat. In each zone, integrated balance equations (mass and momentum conservation) were applied to the gas flow, the liquid film and the dispersed flow. They categorized interactions into four groups: 1) Gas/film interaction; 2) gas/droplets interaction; 3) droplets/droplets interaction; 4) film/droplets interaction. Their model supposes that no mass exchange between the liquid and the gas occurs in the meter (evaporation and condensation). However, atomization of the liquid film was considered at the convergent/throat junction by experimental visualization. A one-dimensional model was proposed which evaluates the influence of the different phenomena occurring between the two pressure taps. The ΔP measurements using the model and experimental results indicated that for the same Lockhart–Martinelli parameter, the characteristics of the liquid film had a great influence on the correlation coefficient.

Regarding the OR models, ISO/TR 11583 [8] adopted a model that was initially introduced by Reader-Harris and Graham in 2009 [33]. In another study, a new correlation for wet gas flow rate measurement with a Venturi meter based on a two-phase mass flow coefficient was proposed [49]. The two-phase mass flow coefficient was found to linearly increase with the Lockhart–Martinelli parameter and decrease with the increase of the gas-to-liquid density ratio. It also decreased with the gas densiometric Froude number increasing. The relationships of the two-phase mass flow coefficient with the Lockhart–Martinelli parameter, the gas densiometric Froude number and the ratio of gas to liquid density were concluded. He and Bai [49] compared the new correlation with some other correlations (de Leeuw correlation [35]; Steven correlation [53]; ISO/TR 11583 correlation [8]). It was shown that the new correlation predicted the wet gas flow rate slightly better than those correlations under the following conditions: the Lockhart–Martinelli parameter ranging from 0 to 0.3, the gas densiometric Froude number from 0.6 to 4.7, the ratio of gas to liquid density from 0.01 to 0.081 and the inlet diameter of the Venturi meter from 50 to 200 mm. The relative deviation of the gas mass flow rate was 2.0 %–3 % under the confidence level of 96.7 %. Collins et al. [54], provided an independent evaluation of public domain wet gas corrections for horizontal Venturi meters, including those published by Murdock, Chisholm, de Leeuw, He and Bai and in ISO TR 11583. In the contrary with [49], it was concluded that

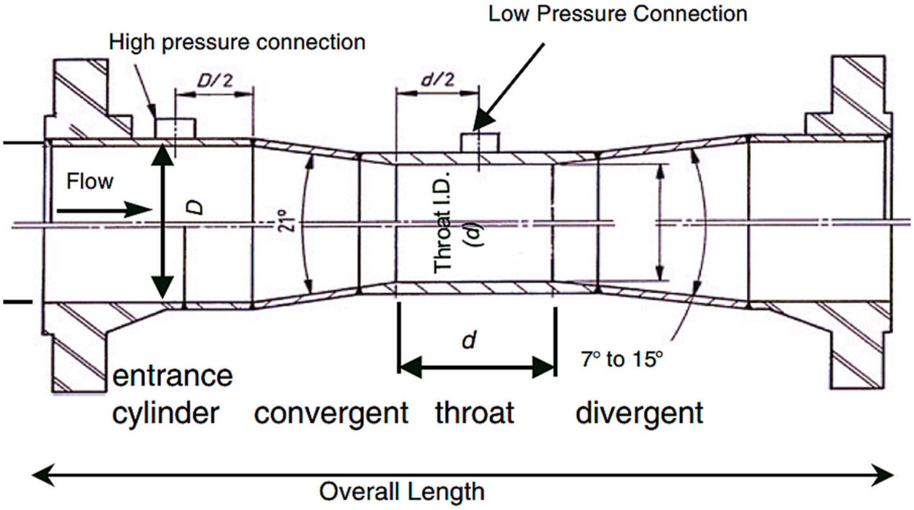


Fig. 7. The classical Venturi tube [37].

the ISO TR 11583:2012 correction significantly outperforms the other standard corrections mainly due to the removal of the bias at low liquid levels seen in other corrections. The same results have been reported by Bjørnera et al. [55]. In a recent wet-gas study, to correct Venturi meter's over-reading, a new correlation was developed to determine the Lockhart-Martinelli parameter from a vertical DP senor [56]. The correlation was obtained by fitting experimental results in TUV-SUD National Engineering Laboratory with nitrogen-water in a 4″ vertical pipe, Lockhart-Martinelli from 0.04 to 0.29, and gas Froude number from 1 to 2.7. Gas flow rate values were obtained within approximately ±5 % error by applying the model with ISO/TR 11583 over-reading correlation.

Graham et al. [57] carried out experiments in a 4-inch, $\beta = 0.6$, Venturi tube with a convergent angle of 21° and a divergent angle of 7.5° which was installed in a horizontal orientation and tested in NEL's new 3-phase wet-gas flow measurement facility at a pressure range of 15–60 bar and X_{lm} 0–0.3. It has been shown from a limited data set that the current wet-gas over-reading correlations in ISO/TR 11583 derived for Venturi meters can be used with reasonable accuracy for 3-phase wet-gas flows. Also, this model performed better compared to the de Leeuw, especially for the higher X_{lm}. Using this method over 85 % of the 3-phase data were within the uncertainty limits of either 2.5 % or 3 % and ±4 for all data ranges. Despite this, it seems that the accuracy of ISO/TR 11583 improves with a decrease in the water cut. However, a detailed comparison of different water cuts in the 3-phase flow was not mentioned.

The vertical installation of Venturi tubes has not been a focus of study or interest among researchers. For example, Hall and Reader-Harris [58] reported that, in multiphase flow, a horizontal orientation of a Venturi tube was the preferred configuration. The reason can be explained by the fact that, while the flow pattern in wet gas is more symmetrical in vertical flow compared to horizontal flow, measuring the necessary differential pressure in a vertical flow is considerably more challenging. This challenge arises because the fluid in the meter line between the two tapping points has a different density than the fluid in the impulse lines. Correcting for the difference in height between the tapping points necessitates a calculation of the average two-phase density in the pipeline, which introduces a degree of uncertainty [37]. Pan et al. [30], investigated the wet gas flow through a vertical Venturi meter. This research fills the vacancy of correlations and presents a new correlation for low pressure between 0.8 and 1.5 MPa with a vertically mounted Venturi meter to calculate the over-reading coefficient accurately. They found that a direct relationship between the over-reading coefficient and quality (gas mass fraction or GMF) had poor performance. The linear relationship between the over-reading coefficient and the Lockhart-Martinelli parameter was also not accurate enough. A new correlation which was a function of the Lockhart-Martinelli parameter, gas Froude number and density ratio to predict over-reading coefficients for wet gas flows was proposed with high accuracy taking gas Froude number under 1.5 into consideration. Based on experimental data, the average relative error, and RMSE were 1.9 %, and 3.0 % which were improved by 33.0 % and 35.0 %, respectively, compared with de Leeuw's correlation. Graham et al. [39] studied the experimental results obtained at the TÜV SÜD National Engineering Laboratory (NEL) for three different Venturi tubes of 4-inch nominal diameter but different diameter ratios (0.4, 0.6, 0.75) installed vertically and subject to wet-gas flow. The results confirmed that the over-reading was not significantly affected by the gas Froude number when the Venturi was installed vertically in contrast with the horizontal one. The over-reading was found to still be enormously affected by the pressure. The results show that the Venturi's diameter ratio had a smaller impact on the over-reading than for the horizontal type. However, the diameter ratio was found still to have a significant effect on the over-reading. Their results confirmed that the ISO/TR 11583 over-reading correlation cannot be employed directly for Venturi tubes oriented vertically.

Additionally, some researchers have attempted to utilize Venturi meters that differ from the standard design. For instance, Zheng et al. [25] proposed a wet gas dual-parameter measuring device composed of a cyclone and a long-throated Venturi tube. Their object was to overcome the difficulty of measuring the liquid content of wet gases and reduce the error caused by the wet gas flow pattern. The flow pattern was transformed into an annular flow pattern by a cyclone. The experiments were conducted at pressure 0.1–1.7 MPa, Q_g 108–260 $m^3\ h^{-1}$, and GVF 90–100 %. The experimental results showed that the traditional wet gas measurement device had gas phase and liquid phase errors of ±4.5 % and ±10 %, respectively while the cyclone-based wet gas measurement device had gas phase and liquid phase errors of ±3 % and ±8 %, respectively. Also, this study introduced a parameter W, which represents the pressure difference ratio between the contraction and expansion sections. Xue et al. [59] developed a theoretical model for the convergent and throat sections of an ETV (Extended Throat Venturi) in a horizontal orientation, and the gradients of front and rear differential pressures were derived analytically. The gas flowrate error of ETV increased with the liquid content whilst the liquid flowrate error of ETV decreased with the liquid content. The relative errors of the liquid flow rate were generally 2 to 3 times larger than that of the gas flow rate. Finally, the ETV tended to be more accurate than the classical Venturi tube. The gas flow rate error was within ±2.4 % and for liquid −8 to 3 %. Recently Xu et al. [60], proposed a precession Venturi with a swirler device at the inlet and established a new OR correlation based on the gas Froude number, liquid-gas density ratio, and the Lockhart–Martinelli parameter. A new OR correlation was proposed in a uniform equation with three groups of coefficients for stratified flow, stratified wavy flow and pseudo-slug flow, respectively. Based on the results, the gas flow rate error was within the band of ±2.94 % with a confidence probability of 95.5 %. The correlation coefficients were classified at different LVF. However, it was not clear how the water fraction itself can be calculated.

It is clear that Venturi have acceptable gas flow rate accuracy. However, when it comes to liquid flow rates, they require more corrections. Despite this, Venturi have shown a fair performance in wet gas flow, maintaining simplicity and cost-effectiveness simultaneously. Regarding the OR issue, several models have been developed with an acceptable accuracy. Nevertheless, there is still room for further modifications and presentation of enhanced correlations. Additionally, the possible liquid accumulation in the upstream and its effect on the response for each flow pattern have not been thoroughly studied.

3.1.1.3. Cone meter. Cone meter is another DP sensor used in wet gas flow, but less frequently than the Venturi meter [2]. It comprises a Cone meter-shaped object which causes an obstruction to the flow, creating a differential pressure across the meter which is proportional to the multiphase fluid flow rate [29]. Instead of contracting the flow, the fluid flows around a central cone as shown in Fig. 8. Similarly, to the Venturi meter, its associated flow equation assumes that the conservation of energy condition is satisfied which requires that the flow should be turbulent.

A tangible advantage of the Cone meter is that it requires only 1 to 3 straight pipe diameters upstream and 0 to 1 downstream to operate effectively. Steven [36] studied the wet gas response of the horizontally installed cone DP meter. A wet natural gas flow correlation for 4 in. 0.75 beta ratio cone DP meters with natural gas, hydrocarbon liquid and water flow was developed from multiple data sets from three different wet gas flow test facilities. This corrected the liquid-induced gas flow rate prediction error of a wet gas flow up to a Lockhart–Martinelli parameter of 0.3, for a known liquid flow rate of any hydrocarbon liquid/water ratio, to ±4 % at a 95 % confidence level. Also, it had been concluded that liquid properties could affect a DP meter's response to a wet gas flow. Wet gas flows with water content generally had a lower liquid-induced gas flow rate prediction positive bias than hydrocarbon liquid wet gas flows and this appeared to be due to the flow pattern at the inlet of the meter.

Zhang et al. [61] proposed a dual-parameter measurement method of gas–liquid two-phase flow based on a dual-cone meter. The two-phase flow was investigated in a horizontal pipeline with $0.00 < X_{LM} \leq 0.05$ and low pressure from 0.14 to 0.19 MPa and exists in the form of an annular flow. By adding a second cone meter, both gas mass fraction (GMF) and mass flowrate were measured. The pressure drop performances of five different-sized cones were discussed. The relative experiment error of GMF, gas mass flowrate and total mass flowrate were respectively within ±7 %, ±5 % and ±10 %. The relative error of the liquid phase was within ±10 % when the liquid mass fraction was beyond 40 %.

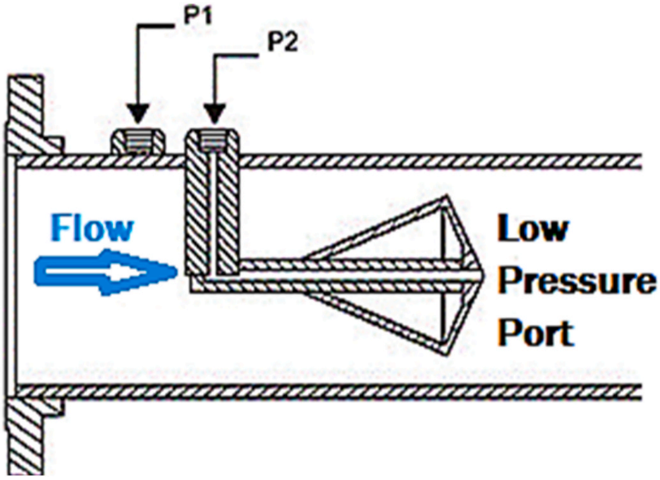


Fig. 8. Sketch of a Cone meter [2].

He et al. [4] developed one Cone meter throttle device for metering both the gas flow rate and the liquid flow rate in wet gas flow. The two-phase mass flow coefficient was employed to correct the measurement deviation of the Cone meter throttle device. The equivalent diameter ratio of the Cone meter throttle device was 0.55. The operating pressure, the superficial gas velocity and superficial liquid velocity ranged from 0.1 MPa to 0.3 MPa, 4.87 m/s to 25.26 m/s and 0–0.38 m/s, respectively and GVF 98–100 %. The results showed that the two-phase mass flow coefficient linearly increased with the liquid densiometric Froude number and was affected by the gas densiometric Froude number and the ratio of gas density to liquid density. The relative error of the gas mass flow rate predicted by the correlations was within ±5.0 % and the mean absolute percentage error was 2.52 %; the full-scale relative error of the liquid mass flow rate was within ±5.0 % and the mean absolute percentage error is 7.03 %. He et al. [62] carried on some experiments on a Cone meter. Their results showed that the vortex length was shortened in gas-liquid annular flow, compared with that in single-phase gas flow. Also, the pressure recovery length was closely related to the vortex length, and a shorter vortex length led to a shorter pressure recovery length. Their results suggested that flow around the apex of the back cone was very stable.

Li et al. [63] presented a new method to measure wet gas flow by combining the Cone device and machine learning techniques. The equivalent diameter ratio of the Cone device was 0.45. Experiments were performed in a horizontal pipe of diameter 50 mm and the operating pressure ranges 100–250 kPa and X_{LM} less than 0.3. The multilayer feedforward neural network was used for developing the measurement model. Moreover, to the mean values of the permanent pressure loss and the upstream-throat differential pressure, the probability density function (PDF) and power spectral density (PSD) of the upstream-throat differential pressure fluctuation were also extracted as representative features. The relative error of the gas flow rate was ±5 % and for liquid flow rates in LVF higher than 0.5 were within ±12 %. However, in a very low liquid loading (LVF less than 0.5) the relative error increased even to 180 %. Zhao et al. [64] investigated the relationships between pressure drop characteristics and entrainment downstream of a Cone experimentally. The equivalent diameter ratio of the Cone was 0.45 with X_{LM} in the range of 0–0.3 pressure 0.1–0.25 MPa and GVF 80–100. The two-phase mass flow coefficient and pressure loss ratio were employed to establish the measurement model. The piecewise characteristics of the pressure loss ratio were disclosed. A simplified method for evaluating the degree of entrainment was proposed to facilitate the establishment of the modified measurement model. Under the experimental conditions, the relative error of liquid fluctuates within ±20 % when X_{LM} was larger than 0.02, and the relative error of gas flowrate was within ±5 %. The problem of large errors for liquid flow rate in low liquid loading was still unsolved.

3.1.1.4. Comparison of DP meters. Based on the literature review, it can be found that there are two different approaches for evaluating Venturi and Cone meter in the case of wet gas. The first time Steven compared these two methods in wet gas flow [65]. He concluded that the Cone meter has advantages over the Venturi meter. The main advantage was that the Cone meter was less sensitive to the liquid loading of a gas flow than the Venturi meter. That was for identical wet gas flow conditions a

Cone meter had a smaller error than a Venturi meter and for a set wet gas differential pressure for each meter type a fluctuating liquid flowrate corresponds to a smaller fluctuation in the gas flowrate for a Cone meter compared to a Venturi meter. When the responses of Venturi and Cone meter meters at the same wet gas flow conditions were plotted on an over-reading to Lockhart-Martinelli parameter graph the gradient of the Cone meter was slightly less than that of the Venturi meter. Graphically this can be seen in Fig. 9.

Fig. 9 shows that for the Cone meter with the steeper gradient, this associated gas mass flow rate error is smaller than for the Venturi meter with a shallower gradient ($\Delta m_{g,\ \mathrm{Venturi}}$). Hence, using a Cone meter instead of a Venturi meter with tracer injection technology gives a lower uncertainty in the gas mass flow rate prediction. In another approach [66], Venturi operated much better than Cone meter in wet gas flow. Li et al. found that while the liquid loading was extremely low, the heights of the liquid film were lower than the minimum clearance between the cone and the pipe, and the liquid phase passes through the cone throat from the gap below the cone or the periphery of the cone [66]. Thus, it can be considered that when the liquid loading is extremely low hence the cone has no significantly enhanced effect on the droplet entrainment. Such responses under extremely low liquid loading conditions are not favourable for the measurement of liquid flow rate using Cone meter.

Finally, it seems that both approaches mention the same results but from different points of view. It can be understood that Cone meter, alone, is not a good choice for wet gas when both gas and liquid flow rates are in favour of measurement. However, Cone meter is the most compact wet gas metering solution that is integrable in most subsea modules. The Venturi solution is more space-consuming but has the advantage that the geometry is less intrusive.

Nevertheless, it would be worthy to compare those devices in a real condition. To achieve this aim, the authors collected experimental data from different literature for Cone meter, Venturi and orifice but almost the same conditions. The comparison was done using experimental wet gas data at NEL where the fluids used are nitrogen (density range 2–70 kg/m^3) and a kerosene substitute (Exxsol D80; approximate density of 800 kg/m^3) at two pressures 15 bar and 60 bar with Fr_g about 2 and X_{LM} range of 0.0–0.3 [36,67,68]. The results can be seen in Fig. 10. Fig. 10a shows results from different devices at a density ratio (DR) 0.024 at 15 bar and Fig. 10b at DR 0.089 and pressure 60 bar. As can be seen from the raw data and without any corrections, the over reading is obvious for all devices. Furthermore, the error in gas flow rate for the Venturi meter is higher compared to the other two devices across the entire range of X_{LM}. However, both the orifice meter and Cone meter exhibit similar levels of accuracy, even under different pressures. It is worth mentioning that although the error is relatively high before any corrections, after the corrections, the error decreases to within ±3 % for all three devices [36, 67,68]. Besides, by increasing the pressure from 15 bar to 60 bar, the relative error for all devices will be decreased especially in the case of Venturi. This observation aligns with the findings of [67], although they did not provide an explicit explanation for this phenomenon. One possible interpretation is that higher pressure levels lead to a reduced density difference between the gas and liquid phases, resulting in improved accuracy for these devices. However, further investigations are required to fully understand this relationship. In conclusion, it is evident that the mentioned devices require correction models to address the issue of over-reading in gas flow rate measurements.

3.1.2. *Flow induced dynamics based methods*

In this section vortex and Coriolis flow meter will be discussed. Although Turbine flow meters can be classified in this category, the operation was proven not to be suitable for measuring wet gas flows [5, 69]. The limitations of Turbine flow meters in wet gas flows can be attributed to two main factors: 1) susceptibility to damage resulting from collisions between the liquid components and the turbine blades, and 2) the potential for wear and tear on the bearings due to the presence of particulates or impurities in the fluid. These concerns do not appear to be exclusive to wet gas scenarios, as they could also pose challenges in single-phase or other two-phase flow situations.

3.1.2.1. Vortex flow meter. Vortex flowmeters are widely used in the measurement of the mist flow for their excellent linearity, high measurement accuracy and wide measuring range [44,67,70,71]. Studies at NEL [72] revealed a qualitative agreement with previously published data (despite different quantitative values due to different fluids and test conditions). The NEL investigation reported an error ranging between 0 and 30 % depending on LVF and gas velocity. As the gas velocity increased, at some test conditions, the holdup/flow regime interacted with the meter so that large fluctuations in the meter error were recorded. Interestingly, as the pressure increased, the apparent flow rate measured decreased due to the reduction in the holdup of liquid, via a reduction in slip. Moreover, the operation of the meter was found to be independent of the gas superficial velocity for many tested values of LVF.

Hua and Geng [73] introduced a wet gas meter, based on a combination of two dissimilar output signals from a swirlmeter, i.e., the vortex precession frequency and the differential pressure of the swirlmeter. There were gas mass flow rate errors within ±8 % from 91.3 % of tested samples, and liquid mass flow rate errors within ±20 % from 89.2 % of tested samples, which may be used to meter both gas and liquid flow

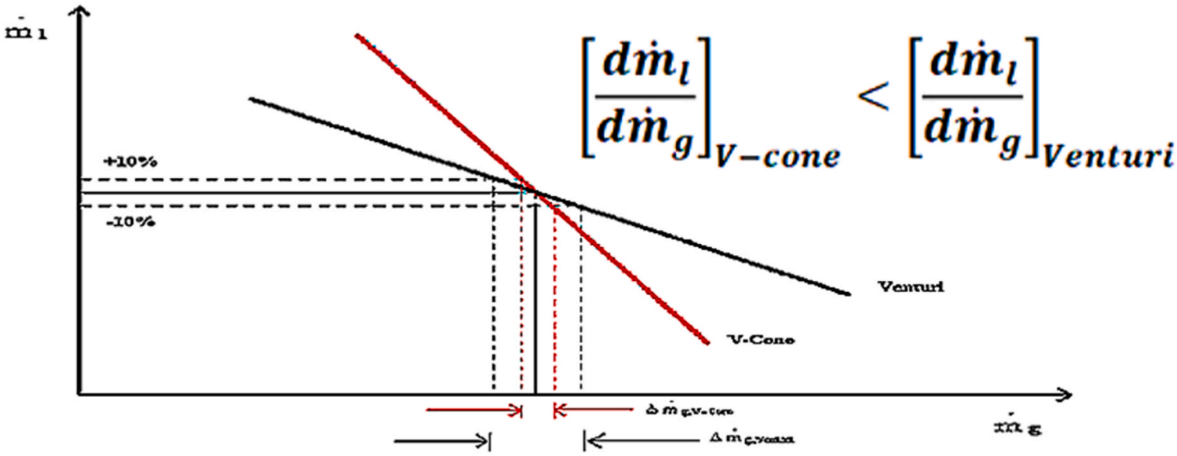


Fig. 9. Constant differential pressure graph showing the Cone meter and Venturi meter relative gas mass flowrate errors due to the ±10 % tracer injection liquid mass flowrate estimation [65].

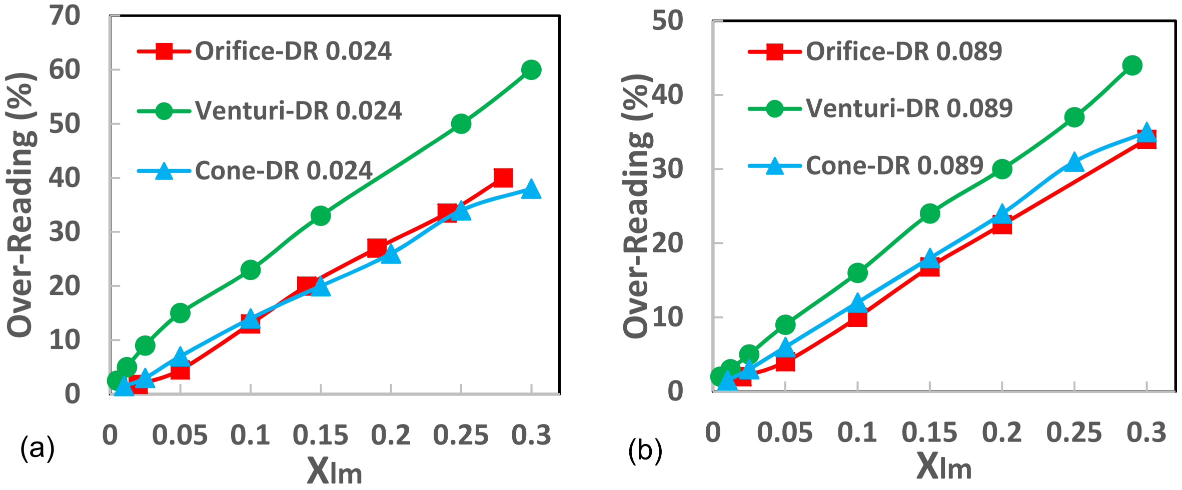


Fig. 10. Comparison of orifice, Venturi, and Cone meter in a horizontal orientation at different pressures a) 15 bar b) 60 bar.

rates for wet gas flow with $X_{lm} \leq 0.12$. The wet gas meter was mounted horizontally, and the gas flow rate was 50–200 $m^3\ h^{-1}$ with Fr_g 0.23–0.83. Wang et al. [74] developed a multi-parameter adjustable mist flow apparatus. The tests indicated that it provides stable mist flow with atomized droplets smaller than 50 μm, and the liquid mass loading can be controlled up to 0.35 at operation pressure ranging from 100 to 700 kPa with Q_g 5–25 $m^3\ h^{-1}$. Time- and Frequency-Domain characteristics of vortex signal were analyzed in detail. The vortex flowmeter experiments on the developed apparatus show that the over-reading of gas flowrate will increase with liquid mass loading and its growth rate was positively related to the operation pressure and Reynolds number. The maximum over-reading was about 1.08 with calibration error for Strouhal number ±1 %, where Strouhal number is defined as:

$$Sr = f.d/u \tag{12}$$

Where u is the average velocity of incoming flow and d is the width of the bluff body and f the bluff body alternatively in frequency.

Li et al. [75] developed a model by using the frequency and amplitude characteristics of a vortex flowmeter in annular mist flow. The low-frequency modulation behaviours of the vortex outputs were analyzed by the ridge method based on continuous wavelet transform (CWT). They found that the averaged ridge method has good accuracy and stability compared to Fast Fourier Transform (FFT) for the feature extraction of vortex signal in annular mist flow. Nevertheless, the authors didn't compare whether the same results could be achieved under different flow patterns. Then, an exponential equation for the dimensionless signal amplitude of the sensor response was developed using droplet mass loading. Lastly, a wet gas measurement model with the simultaneous equations from these two correlations was established. In their study, the percentage errors (PEs) of the gas flowrate predicted by the modeling are within ±1.5 % and the mean absolute PE is 0.37 %. Also, full scale percentage error (FSPE) for droplet mass loading was reported from -10-6%. The same authors [76], to improve the wet gas measurement accuracy by vortex flowmeters installed vertically, modelled the meter over-reading based on the particle-laden vorticity dynamic equation and vorticity transport mechanism. For the experiments, an annular mist flow loop with a film metering device was developed at 100–700 kPa and 9–17 $m^3\ h^{-1}$ gas flow rate. Then, a new over-reading equation was developed by using the scaling group of droplet mass loading ($\phi_p = m_p/m_g$) and macroscopic Stokes number ($St = d_p^2 U_{sg}(\rho_p/\rho_g)/(18\vartheta D)$). The results indicated that the proposed equation provides a uniform prediction for the meter over-reading, the relative deviations were within the ±1.0 % error band. Nonetheless, in both articles, it seems that the uncertainty in droplet mass loading measurement is more than the gas flow rate accuracy itself.

One of the limitations of the meter is the effect of external forces which may alter the vortices generated by the bluff body. This mainly includes pipeline vibrations caused by pumps, compressors, or even pipelines the resonance frequency of which is usually low, but can cause a higher noise effect for low flow velocities.

Sun et al. [77] applied an acceleration probe after the bluff body to reduce the effect of pipe vibration on the output signal. The acceleration probe was installed downstream of the bluff body to measure the amplitude and frequency of the vortex. After that, the acceleration amplitude in wet gas was nondimensionalized by dividing the amplitude in dry gas flow. A correlation between the dimensionless amplitude and the gas Weber number was obtained. Finally, the model was solved based on Newton's iteration to predict the gas flow rate in wet gas. In their study, an error band of ±2.0 % was reported with a MAPE of 0.85 %. However, there wasn't presented any comparison between the classic vortex flow meter which uses a piezoelectric signal with the newly presented accelerator.

In conclusion, further research is needed to explore vortex flow meters comprehensively. Firstly, the impact of the bluff body structure on downstream flow patterns remains unknown. Additionally, the appropriate size of the bluff body is a concern; it is unclear whether it should be small and positioned in the middle of the flow stream or mounted vertically to cover the entire pipe cross-section. The effect of bluff body size on wet gas flow has not been thoroughly investigated to the best of the authors' knowledge. While some research has attempted to extract different parameters, including frequency and amplitude, to determine gas and liquid flow rates, these efforts have been limited to the annular flow pattern. Therefore, further research is necessary to encompass the effect of flow patterns on vortex flow meter performance.

3.1.2.2. Coriolis meters (CMs). Coriolis mass flowmeters were introduced in the early 1980s for natural gas measurements and gained popularity in many gas flow applications in the past few decades due to the meters improved accuracy and the capability of measuring the mass flow rate directly. The first application of Coriolis meters was proposed by Li and Lee [78] for liquid measurement, as the meter was proved successful for mass flow measurement of liquids with reliable accuracy prior to the application for natural gas measurements. Although CMs have wonderful features when measuring liquid flow, and fair characteristics when measuring gas flow [79], the results reported by Stewart [32,72] and Britton et al. [80], presented low repeatability and high errors in the case of wet gas flows, even with a low liquid phase content.

Furthermore, other researchers have verified the low repeatability of Coriolis devices at higher GVF levels (GVF more than 50 %) [81,82]. This has been attributed to a relatively slow measurement update rate (1

Hz) in comparison to the rapid slugging phenomena observed within the experimental setup under such conditions [82]. Lansangan et al. [83], 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 0.8–3.5 MPa; Gas flow rates 0.25–2.5 million standard cubic feet per day; and Gas wetness X_{LM} range 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 %.

Geng et al. [84] used a Coriolis meter in wet gas flow. They investigated different positions for Coriolis and concluded that the horizontal one had a more robust signal than the vertical type. Tombs et al. [82] described the development and testing of a Coriolis two-phase flow metering solution for nitrogen/synthetic oil mixtures with viscosities ranging from 50 cSt to 500 cSt, and with GVF ranging from 0 % to 90 %. Formal trials took place at the UK National Flow Laboratory. The results showed that Coriolis metering was well suited to high-viscosity oil/gas mixtures: in the formalized trials, mass flow errors for gas were mostly within 5 % and for liquid were mostly within 2.5 %. The details of the measurement algorithm or correction method were not mentioned.

Hollingsworth and Morett [85] proposed a new method for wet gas measurement using a Coriolis. The performance of Coriolis meters could be greatly improved by using drive power or drive gain 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 to flow tubes goes into the relative motion between the liquid and gas phases, requiring an increase in drive power to maintain constant tube amplitude. Sharp increases in drive gain are indicative of a two-phase flow. Fig. 11 shows that with as little as 0.027 % liquid by volume, drive gain was a clear and immediate indicator in one Coriolis meter but does not register with the other. Even with half as much liquid, drive gain was still useable as an indicator, although it was a fairly subtle change.

Dayev and Yuluyev [86] proposed an invariant system using Coriolis to measure the wet gas flow. Their measuring system was developed based on a combination of methods of partial flow measurement and the multi-channelling principle. The setup comprises the primary gas flow measurement pathway, featuring a Coriolis flow meter within a measurement pipeline. Alongside this, there exists an auxiliary channel responsible for segregating wet and dry gases. In brief, a parallel system was established, incorporating three Coriolis devices, which predominantly operate through a separation technique. It's noteworthy that a constraint was imposed on the liquid content, stipulating that it should not exceed 5 % in wet gas flow. In a white paper on Coriolis meters presented by the company E + H, smart filtering and diagnostics in a package called Gas Fraction Handler (GFH) was introduced [87]. They mentioned that the filtering technology of the meter output is adaptive and does not unnecessarily dampen or slow down measuring response under normal conditions. It was mentioned that their flowmeters would never stall across the full range of 0–100 % entrained gas and that continuous measurement and output is always provided. Also, the inhomogeneous medium diagnostic index can be used to describe the relative level of the liquid phase in a wet gas application [87]. However, no experimental data were reported especially in the case of wet gas flow.

Meribout et al. [2] 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. It was shown that the bubble model, combined with a two-stage ANN algorithm can help lower the measurement absolute error down to less than 2.5 % for both density and mass flow rate measurement for the whole GVF range. Also, they used drive gain as the input parameter for the first ANN model. They presented that drive gain in Coriolis meters was very sensitive to even small amounts of liquid. Based on their result an accuracy of less than 2 % relative error can be obtained using drive gain. However, it needs an inline separator which is intrusive to flow and their application in the industrial field might be limited.

There is still not sufficient data on wet gas flow using Coriolis. Some points for using Coriolis in the wet gas need to be clarified. Firstly, Coriolis is based on the measurement of the total mass flow so by entering a liquid into Coriolis tubes they should show a big difference from the dry gas flow due to large density differences. It means that those devices should present a fair prediction for the total mass flow rate in a two-phase flow. Certainly, they can be applied to measure the dry gas flow in a wet gas condition by using correction models. Also, there can be different configurations for tubes such as belly down (tubes in the down), belly up (tubes in the up) or even with different angles. Even the optimum length and curvature of the tubes can be different for each company. To the best of the authors' knowledge, the performance of those configurations in wet gas flow hasn't been investigated. Besides, it seems that bent tubes in the Coriolis may cause a severe change in the output flow pattern which needs more consideration.

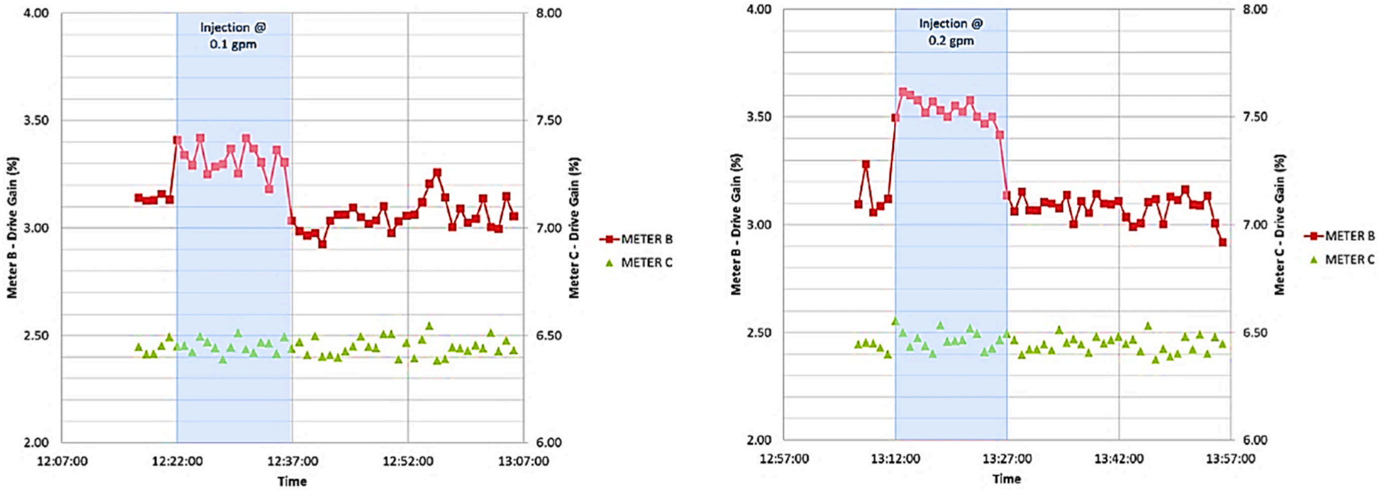


Fig. 11. Drive gain response, 0.1gpm liquid, 0.2gpm liquid injection [85].

3.1.3. Fluid velocity measurement based methods

3.1.3.1. Ultrasonic meters (USMs). Ultrasonic flowmeters have been developed for many years and widely used to measure the flow rates in liquid and gas flows [88]. There are two types of ultrasonic flowmeters based on their operating principle: (1) pulsed and continuous-wave Doppler ultrasonic flowmeters and (2) time-of-flight (TOF) ultrasonic flowmeters. Doppler methods are limited to low void fraction or homogenous two-phase flow and are not applicable for wet gas flow [89,90]. TOF ultrasonic flowmeters calculate the transit time of the ultrasonic signal between the downstream and upstream sensors, which is influenced by the line-averaged velocity along the ultrasonic beam (Fig. 12). A sound wave propagating in the direction of the flow travels at a faster rate than one traveling against the flow. Therefore, by continuously measuring the transit times the difference in the time travelled by these two ultrasonic waves, is directly proportional to the mean flow velocity.

TOF ultrasonic flowmeters can be further classified as in-line or clamp-on types based on the sensor installation. For in-line TOF ultrasonic flowmeters, the ultrasonic sensors are installed at designated points within the piping system. In contrast, for clamp-on TOF ultrasonic flowmeters, the ultrasonic sensors are installed at designated points external to the piping system. In this case, the ultrasonic sensors are removable which makes it more convenient to measure the gas or liquid flow rates at various points in the piping system.

The full ultrasonic theory in a two-phase medium was first derived by Epstein and Carhart [92] who investigated the attenuation of sound in fogs and thus their analysis was based on liquid drops in air. Several manufacturers of ultrasonic flow meters tend to research the metrological characteristics in two-phase flow by using the traditional single-phase USM and since the 1990s there has been considerable discussion about the use of USMs in wet gas metering. This field of research was initiated by Wilson [93], who studied wet gas metering with four-path horizontal ultrasonic flow meters and was further developed by other researchers [94,95].

Zanker and Brown [95] performed the tests at CEESI (USA) using natural gas/decane and natural gas/Texsolve, and at NEL (UK) with Nitrogen/Kerosene in the case of wet gas two-phase flow. The test matrix pressure ranging was from 2.5 to 7.5 MPa, gas superficial velocity (Vsg) from 2 to 20 m/s, and LVF from 0.1 to 5%. It was shown that USMs can be reliable in the presence of stratified flow patterns (when horizontally mounted) and mixed flow patterns (in any mounted orientation). In mist flow, a 1 % LVF gave a 1 % error in an USM, and in stratified flow about 5 % error was reported. However, they emphasized the difficulty of finding universal relationships between LVF and Velocity of Sound, Gain (A measure of the attenuation of the signal), Standard Deviation (Shows the quality of the signal, The presence of liquid mist increases the standard deviation), and Signal to Noise Ratio (SNR).

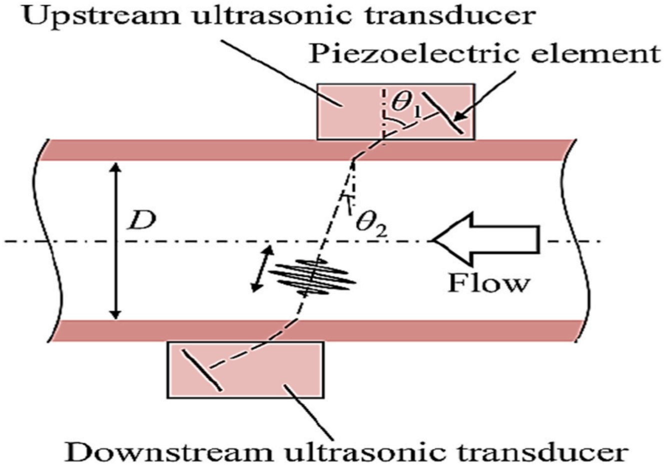


Fig. 12. Ultrasonic meter based on time of flight [91].

Ultrasonic wave propagation effects were observed on several meter diagnostic parameters, and the challenge was to find a simple correlation between ultrasonic signal and pressure, gas superficial velocity and LVF. CIDRA Corporation [96] presented a measurement method which combined a differential pressure-based gas flow meter with a SONAR-based flow meter to provide two independent measurements of the wet gas mixtures. This combination was applied at pressures range of 1.38–6.9 MPa, flow velocities ranging from 6 to 24 m/s, and for X_{lm} less than 0.2. The results showed an accuracy of ±2 % for gas flow rates and ±10 %for liquid flow rates. FLEXIM [97] utilized a clamp-on gas ultrasonic flowmeter to measure wet gas flow in a horizontal pipe. The experimental pressure was 3–7.5 MPa, and the LVF ranged from 0 to 5%. The experimental results showed that the error was less than 8 % and at constant LVF 1 % higher pressure 75 bar) performance was better than lower pressure (30 bar). The tests also confirmed that a substantial amount of liquid can gather at the bottom of the pipe even at an LVF below 5 % due to the fact that the liquid usually flows much slower than the gas at low flow rates. Also, signal loss can be avoided by using a horizontal path configuration to ensure that the ultrasound paths are not interrupted by the higher liquid levels. FLEXIM [97] concluded that careful consideration should be given to the installation location of the ultrasonic. The degree of turbulence (especially close to control valves) can be so high that the signal quality was decreased below an acceptable level.

Xing et al. [98] proposed an error correction model for an ultrasonic gas flowmeter to explore the potential of an ultrasonic flowmeter for metering gas-liquid stratified and annular flows under different test pressures including 0.2–0.5 MPa and the gas and liquid superficial velocities from 4 to 30 m/s and 0.01–0.7 m/s, respectively. A single-path ultrasonic flowmeter was applied, and the error of the apparent volumetric flow rate was considered as mainly resulting from the shrinkage of the gas flow path due to the presence of a liquid phase. It was demonstrated that the root-mean-square error of the gas mass flowrate can be reduced from 19.0 % to 4.6 %, 3.9 %, 3.7 %, and 4.0 % by employing different void fraction models: Lockhart & Martinelli, Baroczy, Spedding & Chen, and Wallis, respectively, within the tested range of flow conditions [98]. Also, Lockhart & Martinelli model was recommended due to its higher accuracy, simpler formulation, sounder theoretical support, and stronger immunity to pressure variation.

The work of Zanker et al. [95] supports the common general thesis that USM operation is strongly influenced by the flow pattern since it affects the local gas velocity. In fact, the results of Wilson [93] also showed a significant difference between the meter response in stratified flow and annular mist flow, both of them characterized by some scatter in the data around the fits. Moreover, no data on the transitional flow pattern for ultrasonic flow meters have been provided yet.

Xu et al. [99], developed a USM over-reading model for determining the gas phase flow rate under certain circumstances, in which the liquid flow rate was assumed known. The experiments at the line pressure range of 0.2–1.1 MPa in two-phase flow were conducted to validate this developed model. A DN80 V-turn one-time reflected two-path ultrasonic meter was used. By comparing the experimental data with the master meters' data, all the relative deviations of the predicted points by the model were within ±15 % and in addition, 88 % of points dropped within the error band of ±5 %. However, the effects of the entrained droplet on the propagation characteristics of the ultrasonic wave were ignored. van Putten and Dsouza [100] introduced an over-reading correction method based on a large data set of ultrasonic measurements in horizontal configuration at conditions comparable to field applications. The correction method could correct the ultrasonic over-reading with an uncertainty of about 4 % for a 95 % confidence interval for a range of conditions relevant to the oil and gas industry. However, based on their conclusion, the presented correction method was complex and not expected to be implemented in ultrasonic flow meters in the field [100].

Murakawa et al. [101] proposed a new signal processing method to determine the transit time difference in a steam flow, particularly at lower signal-to-noise ratios. Two clamp-on ultrasonic transducers were used to measure the ultrasonic time-of-flight, which varied depending on the flow rate. The transmitted ultrasonic signals were time-dependent due to the generation of guided waves in the pipe wall. The standard deviations of the target signals increased when the flow regime transitioned from stratified to annular mist flow. Based on the results, the use of the standard deviation of the target signals was suggested for estimating the transit time difference. Further, as the standard deviation varied significantly depending on the flow regime, it can be used to identify the flow regime as well. Wang et al. [102], based on the single-phase ultrasonic gas flowmeter, proposed the ultrasonic signal clustering synthetic peak (UDCSP) method to process the complex signals in wet gas. It could overcome these defects that ultrasonic signals fluctuate greatly, were easily distorted, and even lost, and also ensure the accuracy of the gas velocity of wet gas. The inner diameter of the measurement pipe was 50 mm and the pressure range of 0.2–1.1 MPa and LVF 0.4–5%. Four ultrasonic probes (two paths) were installed on both sides of the pipe in the form of ‘X’ mode. The angle between each acoustic path and the axial direction of the pipe was 45°, and 1–3 path was in the middle of the pipe, and 2–4 path is located above the middle of the pipe and at a distance of 9 mm from the middle. In the three experiments, the repeatability of the measurement results using the UDCSP method for the gas velocity of wet gas at each working condition was less than 1 % and mostly less than 0.5 %.

Murakawa et al. [91], presented a clamp-on ultrasonic TOF device for measuring wet gas in a steam flow (Fig. 12). The flow rates in wet steam were determined at P = 0.2–0.8 MPa with a wetness fraction less than 20 % (GVF>98 %) within an error of 10 %. They applied a K factor to correct for area-average velocity ($V_{avg} = V_L/K$, V_L stands for the line average velocity along the ultrasonic beam). The error ratio of the flow rates tended to increase with the wetness fraction. They used an average K which probably is not a good choice at different wetness. Additionally, their study was limited to low wetness in the annular and stratified wavy flow patterns. Zheng et al. [103] found that the influence of the liquid phase (even in a trivial amount) on the ultrasonic signals makes the signals' regularity very poor. In order to solve this problem, they proposed a primary envelope normalized cross-correlation method based on the statistical average. The statistical average method was used to overcome the problem of large signal fluctuations. At the same time, based on the analysis of the characteristics of the received signal under different working conditions, the primary envelope of the received signal and the reference waveform were used for cross-correlation calculations. In the working conditions where the gas superficial velocity was from 5 m/s to 20 m/s, and the liquid volume fraction was from 0.2 % to 5 %, the maximum standard uncertainty of this method was 0.5 %. Also, they concluded that when the flow velocity in the pipeline was too high and the LVF was too large, the ultrasonic method had misdetection. Although the amplitude of the signal was used to correct the misdetection, it was easily affected by temperature and pressure [103].

Ultrasonic devices seem to guarantee a powerful method for wet gas flow estimation. Nevertheless, a few questions and concerns need to be considered: 1) the configuration of transducers is a vital parameter to avoid any flooding or blockage in transducers. 2) The effect of different flow patterns on the ultrasonic signal hasn't been investigated thoroughly which might bring a massive difference in the final response. 3) How many paths or channels are sufficient and optimum for the wet gas cases? 4) ultrasonic devices are based on the velocity measurement and finally to convert the results to flow rate needs to account for a modified cross-section. In other words, they need to consider the cross-section where the gas passes not the whole cross-section with some liquids. This might be a little tricky or even difficult to estimate for different flow patterns.

3.1.3.2. Cross-correlation meters. The use of the cross-correlation technique for velocity measurement of multiphase flows has been extensively described by Beck and Plaskowski [104]. The principle of the technique is shown in Fig. 13 as an application of acoustic energy for cross-correlation [105]. Two sensors are used to monitor the flow, one being positioned downstream of the other. These sensors are used to detect variations in some properties of the flow with time such as density, permittivity, conductivity, or sound velocity. The time delay between the output signals of the two sensors can be found by computing the cross-correlation function of these signals (t) and (t) over a measurement period, T. The cross-correlation function is given by:

$$R_{xy}(\tau)=\frac{1}{T}\int_0^T x(t-\tau).y(t)dt \tag{13}$$

Where: $R_{xy}(\boldsymbol{\tau})$ is defined as the cross-correlation function between the outputs from the two sensors which are referred to as $x(t)$ (from the upstream sensor) and $y(t)$ (from the downstream sensor). T is the total time period for which data was acquired (Musbash, 2015).

The transit time of the flow between the two sensors is usually found by observing the time lag $\boldsymbol{\tau}_m$ at which the cross-correlation function is a maximum. A characteristic flow velocity $\overline{U}$ can then be calculated, as:

$$\overline{U}=\frac{L}{\tau_m} \tag{14}$$

The technologies where cross-correlation techniques are often used includes microwave; gamma-ray (density); differential pressure measurements; electrical impedance principles and ultrasound. There is a few research in wet gas flow measurement using cross correlation. For example, Li et al. [106] applied two pressure sensors after a vortex flow meter as a cross-correlator in wet gas flow (see Fig. 14). For the fluctuating pressure measurement, the micro pressure sensors were designed to acquire reliable vortex signals. The system was an annular mist flow loop, and the tests were conducted on a pressure range of 0.15–0.4 MPa, and gas flow rate 15–20 $m^3 h^{-1}$. Then, the dimensionless convection velocity, named convection coefficient, and the peak value of the normalized cross-correlation function, named correlation coefficient were calculated. A function was developed for the convection coefficient with modified Weber number where the segmentation was determined by the correlation coefficient. Finally, the wet gas measurement model was developed and realized by an iterative algorithm. In these conditions, 91 % of sampling points are within ±5 % relative error bands with an uncertainty of 2.8 %.

One of the challenges of the correlation flow meters is to set an adequate value for the distance between the two sensors to handle the widest possible flow rate range. For a long distance, the signals captured by both sensors may not be similar enough, while for a short distance, a very high resolution of the timer is required, which is costly [106].

To sum up, Table 1 shows the main apparent flow rate methods applicable in wet gas flow and summarizes pros and cons of each method.

3.2. Phase fraction methods

These methods can obtain a fraction of each phase not the flow rate. To determine the flow rate of a multiphase flow like wet gas flow, a combination of several sensors is usually envisaged. Gamma densitometers are effective instruments for measuring phase fractions, yet their accuracy becomes a concern in wet gas conditions. Research indicates a notable decline in their accuracy, particularly at higher GVFs [2]. Furthermore, there is limited published data on the performance of gamma densitometers in wet gas conditions, and thus, it will not be discussed in this paper.

3.2.1. Microwave sensor

Microwaves and Radio Frequency (RF) waves are electromagnetic

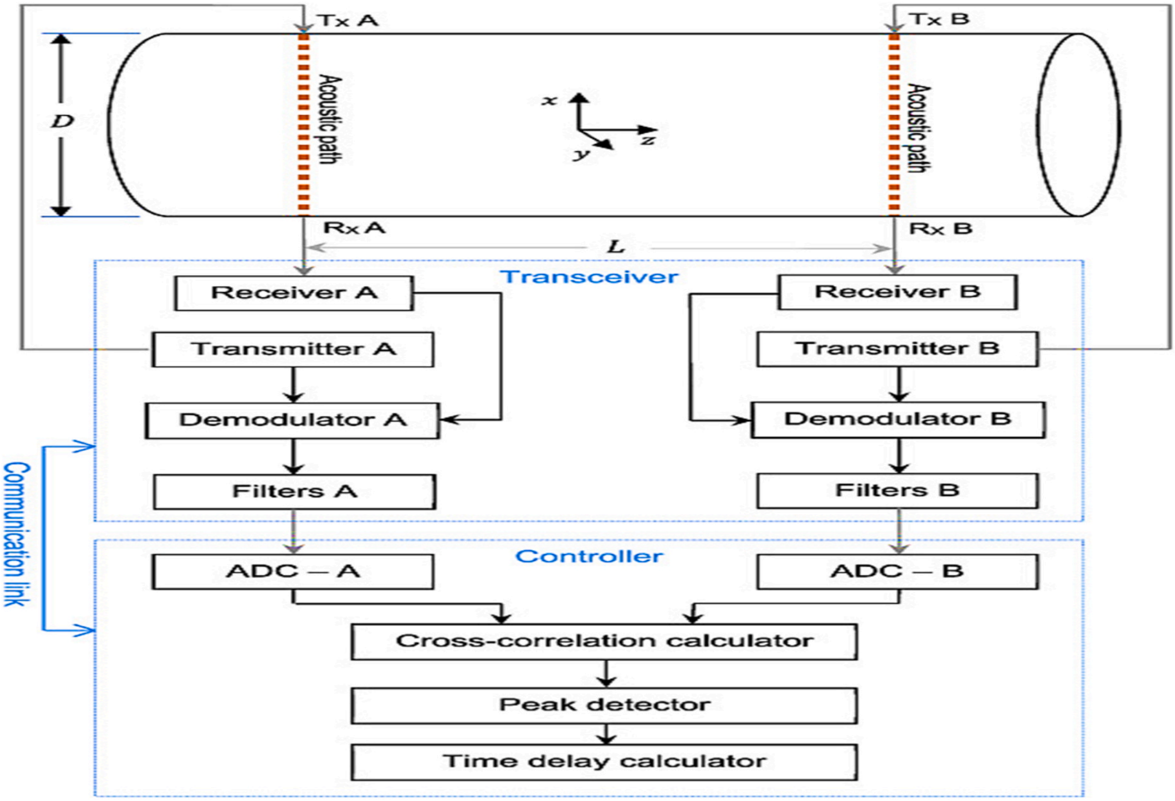


Fig. 13. A schematic diagram of an ultrasonic cross-correlation flow meter [105].

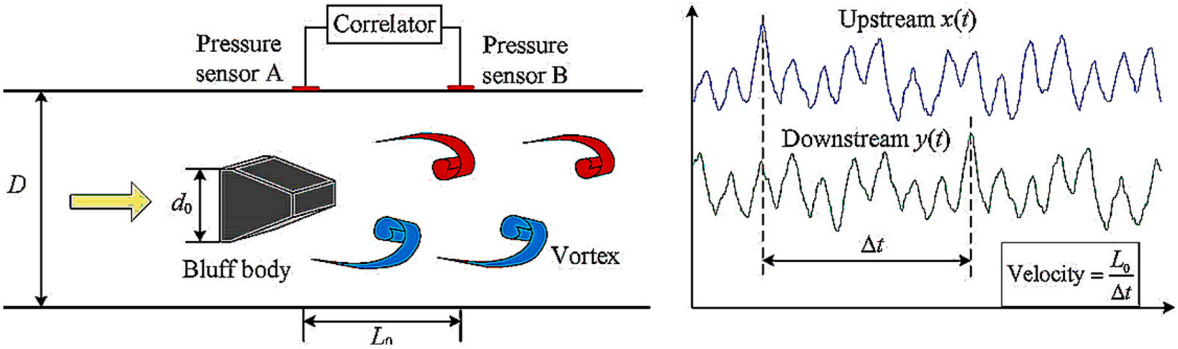


Fig. 14. Diagram of the vortex cross-correlation meter based on fluctuating pressure measurement [106].

waves which can travel in dielectric media. Conventionally, the frequency range of 3–300 MHz is classified as radio frequency (RF) whereas the spectral range of 0.3–300 GHz is considered to be microwave frequency range. However, in practice, the sensors operating either in RF or microwave are generalized as microwave sensors [107].

Microwave sensors are based on the fact that the interaction between microwaves and the tested medium is completely determined by the complex dielectric permittivity (both the permittivity and conductivity affect the propagation behavior of microwaves, i.e., the permittivity relating to the speed and the conductivity relating the attenuation). The relative permittivity (ε_r) or dielectric constant of the material shows its energy storing capacity when a potential is applied across it. Depending on the pipe diameter, the microwave frequencies used usually range from 100 to 5000 MHz. However, lower and higher frequencies are also used. The most common microwave measurement types can broadly be categorized based on transmission, reflection and resonance as shown in Fig. 15. The detail of each measurement method is discussed here.

3.2.1.1. Transmission sensors. In this method, the transmitter and receiver antenna are located behind dielectric walls and facing towards each other. The electromagnetic wave travels between the antennas while penetrating through the flowing media in the pipe. The complex permittivity of the media affects both the phase and the amplitude of the traveling wave [109].

The advantage of this arrangement is the simplicity and even fair sensitivity. But the signal interpretation is complicated. The signal is also influenced by reflections in various parts of the system, like the dielectric walls and other interfaces arising out of flow regimes. These reflections in the system lead to difficulties in signal interpretation and can have an impact on accuracy estimation [107]Nonetheless, it remains a powerful method for water cut measurement. For example, Sheila et al. [110] built and tested a microwave system with two pairs of Patch sensors (transmission sensor) and a coaxial probe (NFP sensor based on reflection) with associated electronics. While the Patch sensor measurement was more effective at low GVF (less than 10 %) NFP was more suitable for higher GVF (>10 %) and the combination of the two helps to

Table 1

Main apparent flow rate metering sensors used in wet gas flow with their respective advantages and disadvantages.

Technology	Advantage	Disadvantage
Orifice Plate	- Low cost and simple to use - No limitation on temperature, pressure, or size - Can measure both liquid and gas flow rate	- Corrosion problems - High-pressure loss (15–55 %) - Liquid tends to accumulate on the orifice wall, until part of it is forced to overpass the orifice. This causes the atomization of water particles flowing through the downstream - It may cause flow pattern changes in downstream - It is not capable of self-cleaning thus can be easily damaged
Venturi	- Simple to use and a natural self-cleaning ability - Causes less pressure drop than orifice plate - Provide reasonable accuracy - Can measure both liquid and gas flow rate - Suitable for medium and large-diameter pipes	- Correction methods have been derived from specific ranges of flow conditions - Not entirely suitable for subsea measurement due to larger volume compared to other DP meters such as Cone meter
Cone meter	- Wide turndown, short straight length - Stable signal - The Cone meter wet gas flow correlation is less sensitive to errors in the liquid flowrate estimation - Due to the geometry of the Cone meter, it prevents the collection of any contaminates as the flow passes through - Manufacturers claim the Cone meter to be highly insensitive to velocity profile effects, thus requiring a much shorter upstream straight	- Cone meter meters require a high Reynolds number to measure correctly - It causes a higher pressure drop than the Venturi meter - The estimation of the discharge coefficient and expandability factor is challenging - The accuracy in wet gas flow is not better than Venturi
Vortex flow meter	- Good turndown - Strong robustness - The meter is more accurate for high-flow rate measurement - Relatively low cost, small pressure difference, no moving parts - Excellent linearity	- The accuracy may be altered by external forces such as pipe vibrations because of control valves, pumps etc, especially for low flow rates - Uncertainty increases with the decrease of Reynolds number - Dependent on installation condition (horizontal or vertical pipelines) - Vortex flowmeter should combine with other meters to achieve dual-parameter measurement of wet gas flow
Coriolis	- Simple design of the transmitter - Can measure both the density and mass flow rate of the fluid - Ability to deal with any slugs of liquid that may be produced by the well - Flexibility in specification and installation	- Low repeatability and high errors when measuring wet gas flows, even with a low liquid phase content - Tendency to over-reading and under-reading of gas flow rate - External disturbances, the tested Coriolis meters resulted in severe calibration errors at the presence of flow pulsations and/or mechanical vibrations at the Coriolis frequency - Operate at relatively low pressure: not adequate for downhole measurement - Relatively costly and cumbersome - Flow regime dependency has not been studied - Changing the flow pattern in downstream is not very clear - There is no indication in studies to date that suggest that decoupling is substantially different in gas-continuous (wet gas) processes
Ultrasonic	- Large range ratio measurement - No pressure loss - High measurement accuracy	- It was proven to have a poor response to wet gas flows, in terms of error and repeatability of results, even with low liquid phase content - It has been shown a significant difference between the meter response in stratified flow and annular mist flow (Dependency on flow regimes) - Poor data on the transitional flow pattern - Scattering the data even in low liquid loading X_{lm}<0.07

estimate WLR over a wide range of GVFs. Two pairs of Patch sensors axially separated provide velocity from cross-correlation. The robustness of the physics-based model for WLR estimation, with simple calibration, was validated across temperatures 25–120 °C, salinity 0–2.5 %, GVF 0–50 %, flow rates 900–23000 kg/h, pressure 0.1–20 MPa and fluid density of approximately 800, 860 and 965 kg/m^3 (API Gravity of 45, 33, and 15, respectively). Accounting for real-time variation in fluid property due to salinity and temperature, through the complex form of the Bruggeman equation improves, the error in WLR estimation by approximately 1 % in the range of salinity and temperatures tested. The cross-correlation system was evaluated across 0–99 % GVF, 0–100 % WLR and 200–20000 BPD (Barrel per Day) range in Southwest Research Institute in the United States. In general, the linear model coefficients between the measured cross-correlation velocity and reference total superficial velocity, are compared favourably with the gas slip models.

Recently, Ma et al. [111] introduced a microwave sensor based on an orthogonal two-dimensional electromagnetic field, based on the principle of coaxial transmission line, for measuring water content varying from 0 to 100 % in gas/water two-phase flow. Two electrodes are orthogonal located inside the sensor constructing an orthogonal two-dimensional electromagnetic field, so that the sensor can identify the flow patterns of stratified flow, annular flow, wavy flow, and slug flow. Based on these patterns, the phase of the sensor response changes with respect to varying water content was further analyzed through simulation by COMSOL Multiphysics software. Static experiments were carried out to verify the simulation results. Due to the limitation of experimental conditions, the annular flow was not implemented. However, the accuracy of water content was just verified by simulation results.

3.2.1.2. Reflection sensors. In the reflection method (or open-end coaxial cable), the amplitude and phase of the reflected electromagnetic wave from the end of the transmission line are investigated. The measurement principle is commonly based on the influence of flowing media on the fringing electromagnetic fields which are in direct contact with it. A typical example is the open-ended coaxial probe, which is used for measuring permittivity over a broad frequency range.

One of the disadvantages of reflection-type sensors is the small sensing volume. Because of that, it is sensitive to drift due to deposits over it. Also, due to the small local sensed volume, it is not a suitable principle for inhomogeneous mixtures [112]. This system may be suitable for emulsions of water and oil with little liquid drop size as the presence of a small volume affects the measurement [113].

3.2.1.3. Resonator sensors. The resonance frequency of a microwave resonator is related to the permittivity of the media in the resonator. By measuring the resonance frequency, the permittivity of the flowing media can be estimated [114]The principle of the microwave resonance cavity is that the electromagnetic field confined in the closed or open cavity produces resonance phenomenon, the resonance frequency of the

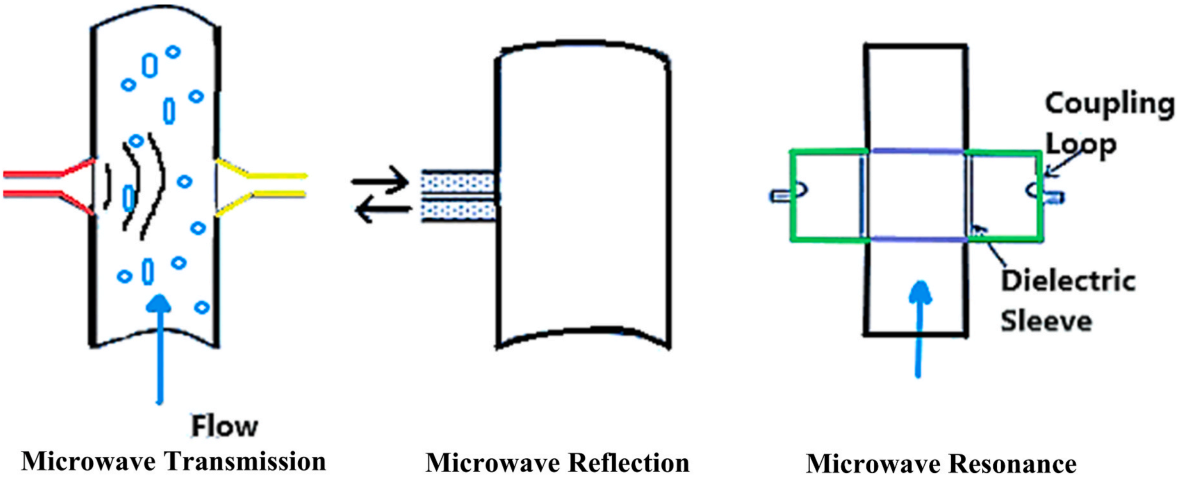


Fig. 15. Categories of microwave measurement methods [108].

microwave cavity obtained by detecting single-port or two-port network parameters S_{11} and S_{21} can reflect changes in the water volume. Resonance-based measurements are quite sensitive to even small changes in permittivity; however, this can also be a drawback when a wide range is to be measured [115]. One of the distinct advantages of the resonator-based sensor is that it is relatively robust as compared to the amplitude and phase measurements. Because microwave resonators are inherently stable and the resonant frequency and quality factor (Q-factor), which are the two measurable properties of a resonance, can be measured with high accuracy, the microwave resonance method is one of the most sensitive and accurate method available for measuring the water volume fraction of a wet gas flow [114,116].

In the case of wet gas, literature results show good linearity in response to resonance cavity. For example, Al-Kizwini et al. [117] investigated annular two-phase flow in the case of water-air and oil-air two-phase flow using microwave cavity resonance. They found a very good linearity when GVF is more than 80 %. They performed a static experiment, and they did not compare their results in different flow regimes. Similar results have been reported by Oon et al. [118] (Fig. 16). Another vital issue that they included in their study was the temperature effect on the sensor's response. It was shown that no frequency shift was observed up to the temperature of 83 °C (Fig. 17). The temperature of the water varied between 28 °C and 83 °C and it did not affect the accuracy of the system, despite the permittivity of water changing with the temperature. However, in order to prove the temperature independency of microwave sensors, further research work is required in the case of both air-water two-phase systems. Also, both the temperature and conductivity of the measured fluid would affect the permittivity, which could be included in the investigations. Yang et al. [119]studied and simulated a microwave cavity resonance for the measurement of low water volume fraction. The static experiment of the gas/water two-phase medium was carried out. The inner diameter of the cavity was 100 mm, the outer diameter was 130 mm, the diameter of the central opening of the cavity was 50 mm, and a pair of holes was opened on one side of the cavity for antenna installation. The axial length of the cavity was 18 mm. The results showed that the sensor can detect the change of two-phase medium with 0–10 % water volume fraction. And within the range of 0–10 %, the relative error was less than 7 %. However, the spatial distribution of fluids may also affect the permittivity of a mixture; thus, the flow regime is one of the key factors affecting the measured apparent permittivity. Despite of microwave importance in fraction measurement, there is not sufficient data on the accuracy of this

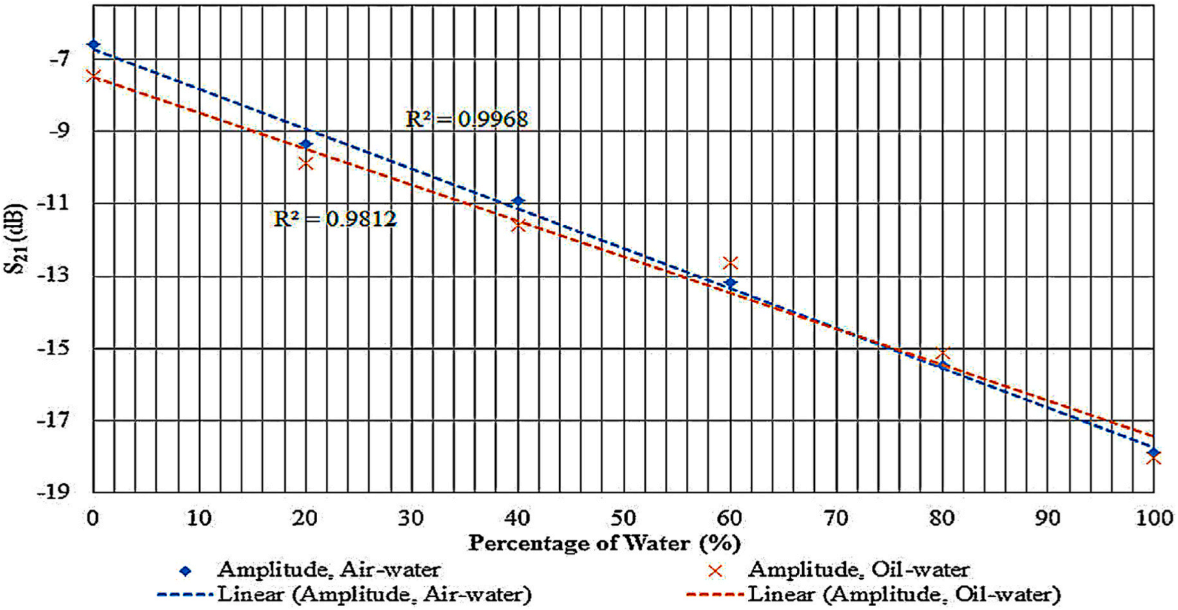


Fig. 16. Relationship between the change in the volume fraction of water and amplitude in two phase systems [118].

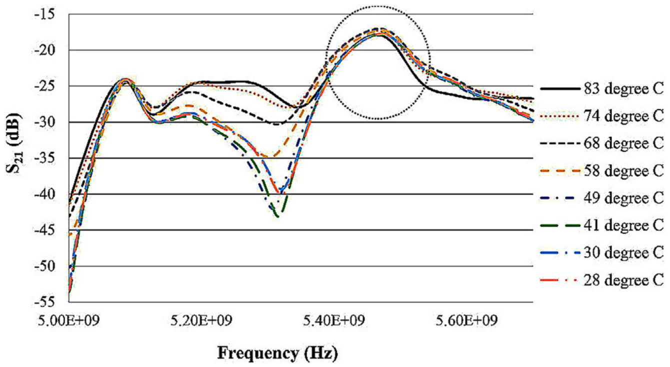


Fig. 17. Graph of S_{21} (dB), showing the frequency at different temperatures for 100%water [118].

method for wet gas flow.

3.2.2. *Impedance sensors*

The basic principle of impedance sensors for multi-phase flow measurement is that the different phases differentiate in the electrical characteristics, *i.e.,* the conductivity, permittivity, or permeability. A voltage with a lower frequency compared to microwave ranging from sub-hertz to megahertz is applied between electrodes and the sensing response is measured. Different methods of impedance sensors are shown in Fig. 18. This report is not going to cover all these methods but the methods most applicable in wet gas flow.

Due to the inherent characteristics of water-air two-phase flow, conductance-based methods are favourable in the case of wet gas, when water constitutes the main liquid fraction. There are different configurations in conductance measurement (Fig. 19), but the basis is the same. They consist of two electrodes (sometimes 3 or more electrodes for measuring conductivity): one as an exciter and the other receiver. The operation of the electrical conductance technique in water/gas two-phase flows relies on the fact that the conductivity of the mixture depends on the gas volume fraction in the water.

The conductance sensor has the advantage to be safe and even a fast dynamic response. However, it is flow regime dependent and therefore not adequate to operate in case the flow regime is not known. Otherwise, a flow homogenizer, such as a Tee junction, is required [2]. Another limitation of the sensor is its sensitivity to changes in fluid dielectric properties which do not remain the same (e.g., during the lifetime of a well) which may cause some systematic errors. Besides, the high-pressure (up to 15 MPa) and high temperature (up to 150 °C) tolerance when installing the sensors can cause an issue [121].

Another limitation of this probe is its limitation to operate in wet gas flow since it usually uses low-frequency voltage or current excitations (i.e., usually in kHz range), corresponding to large wavelength EM waves which are not sensitive to small size water droplets, often found in wet gas fluid [2]. However, several researchers and even manufacturers applied this method as a water fraction measurement for wet gas flow which will be discussed in sections 4 and 5.

In wet gas flow, a conductance sensor is usually accompanied by a phase velocity meter to obtain flow rate measurements of liquid and gas. For example, in wet gas flow, Tan et al. [122] used a cone meter accompanied by a conductance sensor, Musbah [26] studied Venturi plus six ring conductance and recently Sun et al. [123] applied a vortex flow meter and conductance sensor. Their results are shown in Table 3. The conductance method which is applied to measure water fraction has an accuracy limitation for wet gas. Typically, the best relative error in water fraction of wet gas flow is not less than 5 % [26,121].

3.2.3. *Near infrared (NIR) absorption*

Near-infrared light generally refers to light within the wavenumber range of 12,500 to 4000 cm^{-1} (wavelengths from 800 to 2500 nm). Absorption of near-infrared light, like that of mid-infrared light, is based on the vibration of the material [107]. However, near-infrared light absorption is much weaker in intensity as compared with mid-infrared light absorption, since near-infrared light absorption is based on overtones and combined tones in the mid-infrared light region [136]. The light is transmitted, directly or diffusely reflected and absorbed. The light is collected and sent to a detector. The sample can be identified by measuring the amount of light reflected from that [137].

The principle of measuring the phase Volume content ratio of NIR light is based on the Lambert-Beer absorption law and the law of superposition of absorbance characteristics [137]. A beam of monochromatic parallel light illuminates a uniform light-absorbing medium,

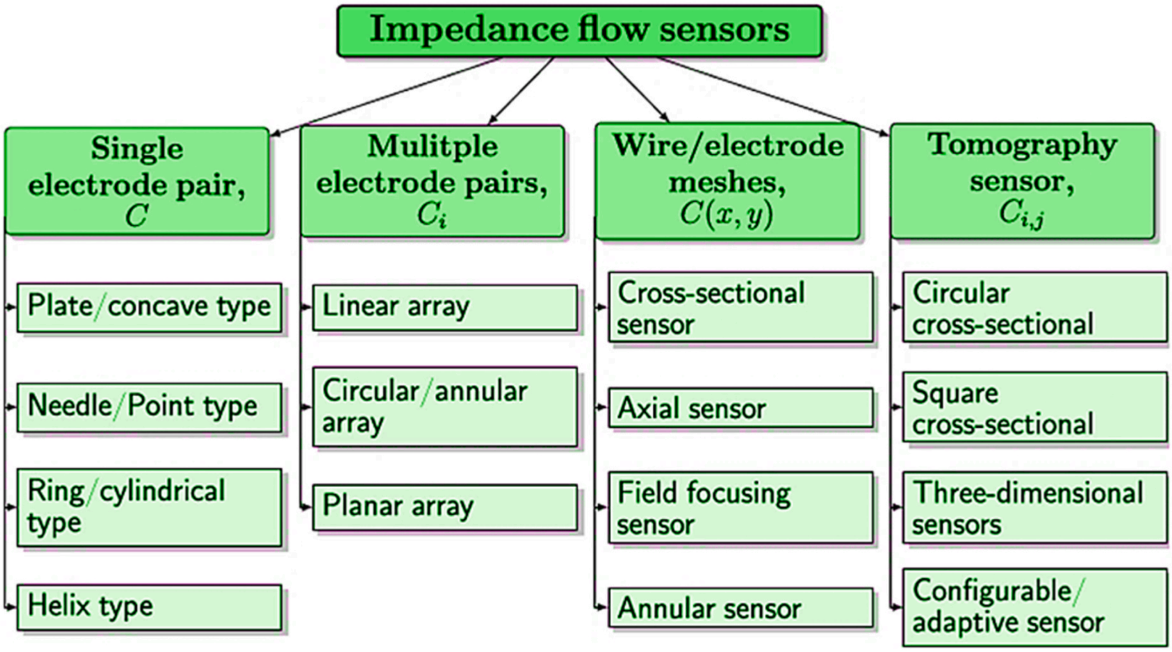
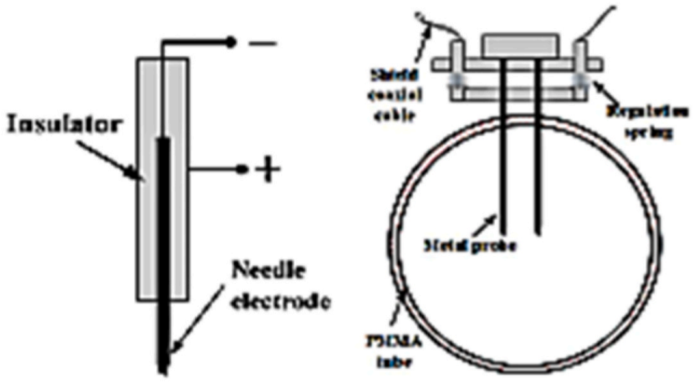
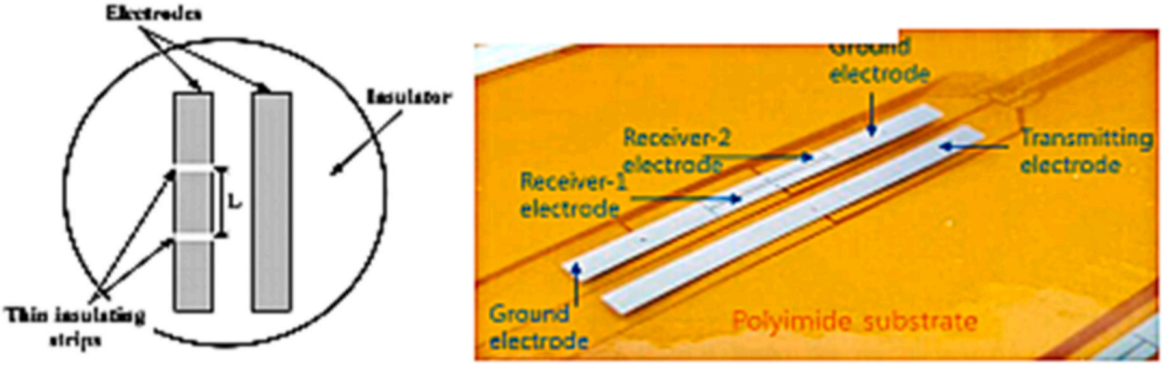


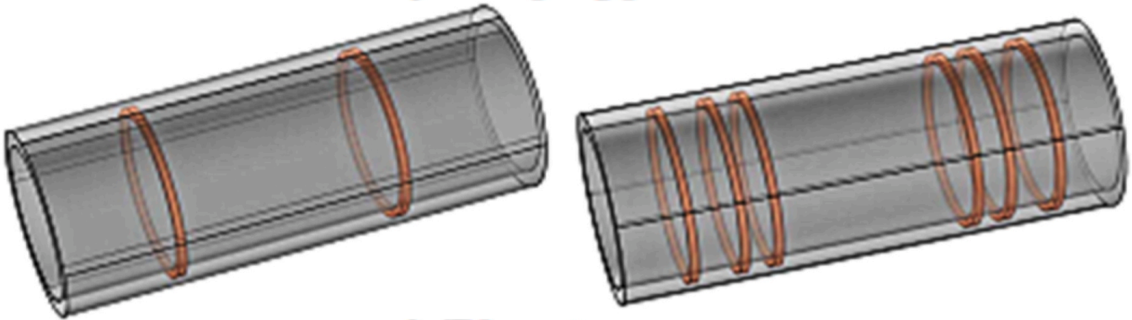
Fig. 18. Classification of Impedance flow sensors [120].



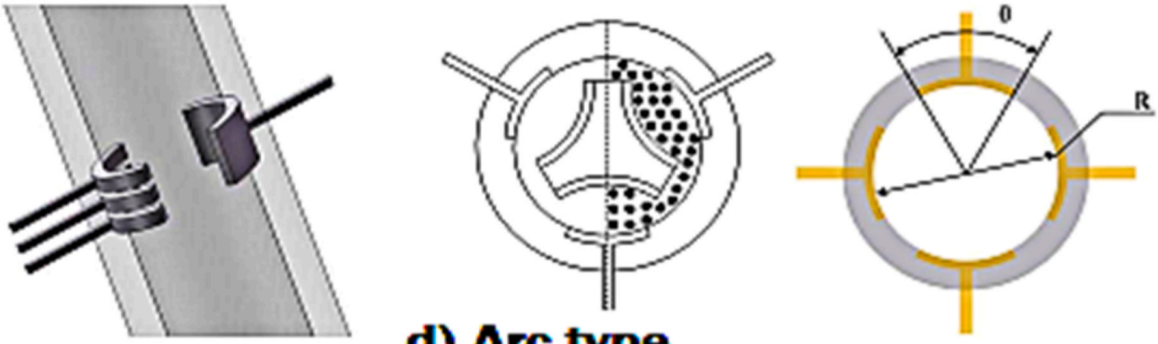
a) Needle type



b) Strip type



c) Ring type



d) Arc type

Fig. 19. Sensor configurations of the conductance probes [120].

for which the relationship can be expressed by Lambert-Beer law as:

$$I = I_0 e^{-\alpha_{\Delta}(\lambda) l} \tag{15}$$

where I_0 and I are incident light intensity and transmitted light intensity, respectively; l is media thicknesses (cm) and $\alpha_{\Delta}(\lambda)$ is the absorption coefficient of light with a wavelength of λ (cm^{-1}). Since the absorption is based on the water molecule itself, there is very negligible sensitivity to

Table 2
Main phase fraction sensors used in wet gas flow with their respective advantages and disadvantages.

Technology	Advantage	Disadvantage
Microwave	- See a very good contrast between water and most other materials, making them well suited for water content measurements - Microwave resonator sensors are inherently stable because the resonant frequency is related to the physical dimensions - Insensitive to environmental conditions, such as water vapor and dust - Less sensitive to build-up than capacitive sensors - The influence of the DC conductivity often disappears - Not sensitive to water salinity	- The higher frequency, the more expensive - Must be calibrated separately for different materials - The temperature variations on microwave response have not been investigated thoroughly - Dependency on flow regimes have not been studied thoroughly - Microwaves penetrate all materials except for metals. Thus, the pipe under test should be non-conductive.
Conductance sensor	- Without or with interference to the process - See a very good contrast between water and most other materials - Low-cost - Easily certifiable to operate in hazardous areas	- Very sensitive to electrode configuration - Cannot detect droplets due to low frequency and high wavelength - Not applicable for nonconductive flow - Dependency on flow regime - It needs corrections by increasing temperature
NIR	- High time and space resolution - Can measure multiple component fractions	- Small iris and slot size which may not represent well the full fluid, could lead to large errors especially for inhomogeneous mixture

water chemistry issues like salinity [2]. As an example, in Fig. 20, by employing advanced chemometrics algorithms, the relative concentrations of water, oil, and methanol can be simultaneously ascertained using five wavelengths (λ_0 to λ_4). In practical scenarios involving high gas volume fraction applications, it is advisable to position the probe near the wall of the pipeline, as the liquid phase is more likely to pass by this particular region. Furthermore, while the gas phase exhibits zero absorption at low pressures (i.e., pressures below 35 bars), it demonstrates a negligible, linear, and composition-independent absorption at high pressures [2].

In recent years, NIR technique has been applied for detection of two-phase flow. Fang et al. [138] used the NIR technique to determine flow patterns of gas–liquid two-phase flow and Vendruscolo et al. [139] developed a NIR optical tomography system for real-time monitoring of gas–liquid two-phase flow. In the case of wet gas, studies are more limited. Wang et al. [140] presented a void fraction measurement method in annular flow based on NIR spectrum. According to characteristic O–H absorption band of H_2O, 970 nm was selected as the emission wavelength of NIR light source. Based on absorption of liquid film, scattering of entrained droplets and interface reflection of two phases, a void fraction model based on NIR transmittance was constructed and further simplified. Utilizing the simplified model and designed non-invasive sensor, void fraction measurements was obtained for 48 horizontal wet-gas annular flow conditions in the pipeline pressure of 0.4 MPa and 0.5 MPa and GVF 0.85–1. Laboratory results indicated that the relative deviations of the measurement model range from 5.53 % to 7.34 %, but the 93.75 % of relative deviations were within ±5 %. Zhu et al. [141] investigated the effect of pressure on wave behavior in horizontal wet-gas annular flow. They used NIR technology in a 50 mm inner pipe diameter at five pressures varying from 0.1 MPa to 0.5 MPa. The probability density function (PDF) and wavelet energy of transmitted light intensity signals were analyzed. It was concluded that the higher pressure induces a bigger shear force at the gas-liquid interface, which plays a leading role in the formation of the entrainment of liquid droplets in the gas core and then leads to an increase in wave velocity. Analysis of PDF and wavelet energy indicated that the increasing pressure led to the distribution range of transmitted light intensity amplitude gradually becoming narrow and the wavelet energy tended to uniform. It means that the pressure could induce the interface flatter and smoother, the wave amplitude smaller and the flow field more stable.

Recently, Zhao et al. [142] measured the film thickness of annular flow at four pressure conditions using NIR sensor. The signal was processed by variational mode decomposition, and the envelope spectrum and Pearson correlation coefficient judgment criteria were accepted for signal reconstruction. In this way, the value of the liquid film thickness was obtained. The effect of flow rate, pressure, and entrainment of the liquid film thickness were analyzed theoretically. Four parameters of We_g, We_l; Weber numbers for gas and liquid respectively;, $N_{\mu 1}$ (dimensionless viscosity) and $X_{LM\text{-}mod}$ (modified Lockhart-Martinelli number) were selected to develop the average liquid film thickness, and a new prediction correlation was proposed. The laboratory results indicated that the mean absolute percentage error of the predictive correlation was 4.35 % (their data) and 12.02 % (literatures data) respectively. One of the main challenges of using NIR for multi-phase application is their high absorption in water or oil phases which requires that the distance between the emitter and receiver should be very small. This may cause significant uncertainties if the sampled medium does not represent well the actual multiphase flow [2].

3.2.4. *Summary of phase fraction methods*

Conductivity sensors may not function effectively in multiphase flows where there is an insufficient water content. This limitation becomes apparent in wet gas flows, particularly those with hydrocarbon condensates, as they often exhibit relatively low water phase fractions [15]. Conductivity sensors are considered suitable for high liquid loading and relatively high Water Liquid Ratio (WLR) multiphase flows [15]. In this scenario, a combination of conductance and capacitance sensors could potentially address the issue effectively.

Systems using microwave sensors, conductance methods or NIR measure proportion of phases visible in the system at the moment of measurement. Each measurement represents a momentary snapshot of the phase ratio at the time it’s recorded. As a result, these devices primarily determine parameters like “Void Fraction (α)" rather than directly measuring the actual phase flow rate fractions (such as Gas Volume Fraction). The actual phase flow rate fractions are computed by comparing the output from the phase fraction device with the output of a flow rate meter such as DP meter using a semi-empirical slip model [15]. Table 2 presents these phase fraction methods applicable in wet gas flow and summarizes advantages and disadvantages of each method.

4. Hybrid technologies for wet gas measurement

There are some points for accurate measurement of both liquid and gas phases in wet gas flow for instance in allocation. Also, when the liquid flow rate changes frequently or no flow rate information is known, both liquid and gas phase flow rates are required to be metered. Three approaches can be suggested for the measurements.

1) Use a single-phase flow meter and extracting different parameters with a powerful correction algorithm or combination of algorithms with an acceptable accuracy for measuring both phases.
2) Use a combination of a single-phase flow meters meter with one or more phase fraction method(s).
3) Arrange two or multiple single-phase gas meters in series, each responding differently to wet gas flow.

Table 3
Recent hybrid methods for wet gas flow measurement.

Literature Source	Method	Range of the test condition	Position	Relative Error	Results
Johansen et al. (2007) [124]	Extended Throat Venturi and Sonar array and NIR	$P = 1.4–5.5$ MPa $0.00 < X_{lm} \leq 0.26$ $Fr_g = 0.5–5.5$	Vertically	Total and Gas flow rate ±5 Liquid flow rate ±20	In low pressure highly unsteady slugging flows, there is a reduction in Sonar measurement capability and hence the measurement performance is reduced. This was evident between 80 and 97.5 % GVF in the multiphase facility.
Hasan and Lucas (2011) [125]	Venturi and Conductance	$D = 80$ mm $P = 0.2–1.1$ MPa $U_{sg} = 6.3–8.5$ m/s $U_{sl} = 0.010–0.016$ m/s $Fr_g = 0.2–0.35$	Vertically	Gas flow rate ±2	It was found, in general, that the gas volume fraction at the inlet of the Venturi is greater than the gas volume fraction at the throat of the Venturi. The optimum value of the gas discharge coefficient was 0.932.
Xu et al. (2013) [50]	Venturi and Cone meter	$D_1 = 80$ mm β (Venturi) $= 0.4$ β (V-cone) $= 0.48$ $P = 0.2$ MPa $U_{sg} = 7.07–21.9$ m/s $U_{lg} = 0.06–0.42$ m/s GVF = 99–100 %	Horizontally	Lab. : Gas flow rate ±3 Liquid flow rate ±6 Test Field: Gas flow rate 1.37–3.22 Liquid flow rate ±10	The correlations were based on the gas densiometric Froude number, gas–liquid density ratio, and the differential pressure ratios, which were then compared and validated by the laboratory and field tests.
Xing et al. (2014) [98]	Ultrasonic and Coriolis flowmeters	$D = 50$ mm $P = 0.2–0.5$ MPa $U_{sg} = 4–25$ m/s $U_{sl} = 0.02–0.7$ m/s $0.03 < X_{lm} \leq 1.3$	Horizontally	Gas flow rate ±5 Liquid flow rate ±5	It was a feasible way to measure the individual mass flowrates of gas–liquid two-phase flow of low liquid loading under stratified and annular flow regimes by combining the ultrasonic and Coriolis flowmeters
Musbah (2015) [26]	Venturi and Conductance	$D_1 = 50$ mm $D_2 = 30$ mm $U_{sg} = 4–8$ m/s $Fr_g = 0.2–0.7$ m/s	Vertically	Gas flow rate ±5	It was found that the homogenous model, assuming no slip, results were better than the Abbas model, de Leeuw and Murdock models.
Sanford et al. (2019) [126]	Vortex flow meter and Cone meter (Vorcone)	$Re = 10^6–6 \times 10^6$ $1.0 < X_{lm} \leq 0.15$ $Fr_g = 3.6–9.2$	Horizontally	Gas flow rate ±2	In saturated steam and wet natural gas flow applications this hybrid meter can predict the two-phase flow quality, and total mass flow rate.
Sun et al. (2022) [123]	Vortex flow meter and Conductance	$D = 15$ mm $P = 250$ kPa $U_{sg} = 18.86–37.73$ m/s $U_{sl} = 0.0028–0.028$ m/s LVF = 0–0.16	Vertically	Gas flow rate ±1.5 Liquid flow rate ±5	By introducing the Weber number of gas and liquid phases, the functional equations of liquid film thickness and meter OR in wet gas two-phase flow were developed
Zhang and Li [127]	Vortex flow meter and Orifice	$D = 50$ mm $P = 200–400$ kPa $Q_g = 80–130$ m^3/h $U_{sl} = 0–0.09$ m/s	Horizontally	Gas flow rate ±5	Measure the gas phase volume flow using the vortex flow meter and then incorporate it into the over-reading model of the orifice flow meter

In the first case, to the best of the authors knowledge, there has not been introduced such a single-phase flow meter. There might be still ongoing research to achieve this important goal which is more favourable to industries. However, there are several research published for cases 2 and 3. Fig. 21 shows the most significant works applied in wet gas flow (cases 2 and 3). Also, Table 3 shows the details of such hybrid measurements. In summary, microwave is the predominant technique for fraction measurement in wet gas flow, followed by the less commonly used conductance method. For flow rate measurement, Venturi and vortex flow meters continue to be the most frequently employed methods. Also, in the case of accuracy and based on the literature result, vortex flow meters have shown better accuracy for wet gas flow compared to other methods [123]. Additionally, some works applied more than two methods. For instance, Johansen et al. [124] utilized Venturi in coupling with Sonar sensor array and NIR. The Sonar flowmeter consisted of an array of electronic strain gauges (non-fibre optic) combined with fully integrated data acquisition and processing electronics housed in a spool-mounted enclosure. The combination of a differential pressure meter with a Sonar flowmeter offers an over-reading contrast that is exploited to yield the total and gas flow rates and the liquid content. They found that, in wet gas conditions, the calibrated Sonar velocity led to a volumetric flow rate that was slightly higher than the actual mixture velocity. The over-reading of Sonar was well-behaved with respect to liquid loading and was readily correlated with the Lockhart-Martinelli parameter [124].

The orientation of the metering instrument could have an impact on the accuracy. This distinction appears to arise from the flow regime dependence of the methods. In vertical pipes, the flow regime tends to be predominantly annular or mist-annular. Conversely, horizontal pipes exhibit a broader spectrum of flow regimes, including stratified, wavy, slug, and annular patterns. These variations might influence the accuracy of metering when operating across different flow regimes. Regardless, a more comprehensive investigation is necessary to elucidate the flow regime dependency of each individual method. Recently, Zhang and Li [127] introduced an approach to address wet gas flow measurement through the combined utilization of a vortex flow meter and an orifice. The core idea behind this approach is to measure the gas phase volume flow using the vortex flow meter and then incorporate it into the over-reading model of the orifice flow meter. The Chisholm model was applied for Operating Range (OR) estimation, enabling them to derive the liquid flow rate. Subsequently, this liquid flow rate was employed to calculate the adjusted gas flow rate. However, the method by which the liquid flow rate was determined remained unclear. Moreover, the study applied a simple void fraction model for mixture density and viscosity measurement, but it notably lacked any slip corrections. Despite this, the reported relative error for gas flow stood at 5 % across a significant portion of the experimental data. Nonetheless, the endeavour of using two flow rate meters in series did not yield a substantial advancement, raising questions about the practicality of this approach.

Table 4
Some Commercially available wet gas flow meters.

Manufacturer	Meter	Fraction Measurement	Flow rate Measurement	Application Range	Temperature and pressure specification	Reported Accuracy
AGAR [128]	Gas Mass Flow Rate	Microwave	Coriolis/Dual Venturi	GVF 0–100 % Water-cut 0–100 %	Up to 24 MPa (0 °C–100 °C)	Liq. ±2–5% Gas ±2–5%
Weatherford [129]	Alpha VS/R	Red eye water cut (NIR)	Extended-throat Venturi Sonar flow meter	Whole GVF-but accuracy better in GVF 99–100 %	Up to 20.6 MPa −40 to 70 °C	Liq. ±20 % Gas ±5 % (GVF 90–100 %)
Emerson (Roxar) [130]	Subsea-wet gas meter	Microwave Resonance	Cone meter	85 %–100 % GVF, and 0 %–100 % Water cut	Up to 68.9 MPa −40 °F (−40 °C) to 302 °F (150 °C)	Water fraction: GVF >98 %: ±0.1 abs. vol % GVF <98 %: ±0.2 abs. vol % Total hydrocarbon mass flow: ±5 % relative Gas volumetric flow rate: ±3 % relative
EMCO Control [131]	Series WG-V	–	Venturi	GVF 90–100 %		Liq. ±10 % Gas ±3 %
HAIMO [132]	Wet gas meter	Gamma ray	Venturi	90–100 % (GVF)	0–35Mpa −50 to 150 °C	Gas Mass Flow Rate 2 % Total Mass Flow Rate 3 %
KROHNE [133]	WGS3000	Water cut meter	Venturi	90–100 % GVF	−40 … +120 °C ANSI 150 Up to 18 MPa	Liq. ±5 % Gas ±1–3%
Pietro Fiorentini [134]	Xtream S	NIR	Venturi and cross correlation	0–100 % WC, 95–100 % GVF	up to 35 MPa up to 150 °C	Liq. ±3 % Gas ±5 %
AMETEK (Solartron) [135]	Dualstream 3	Microwave	Venturi	0–100 % WC, 90–100 % GVF	−20 °C ≤ T ≤ 60 °C	Liq. ±10 % Gas ±2 % Water volume fraction ±0.1 % abs

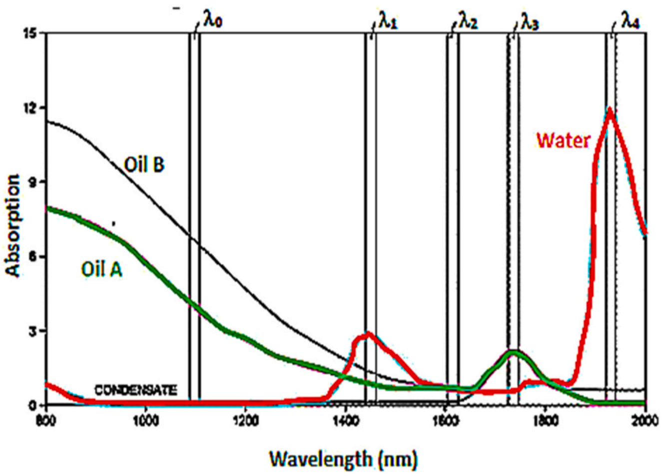


Fig. 20. NIR Absorption spectrum of water and oil [2].

5. Commercially available wet gas solutions

Table 4 provides an in-depth comparison of some commercial wet gas meters. Notably, Microwave technology emerges as the primary choice for fraction measurements, followed by the less commonly employed NIR technique. In the realm of flow rate measurement, Venturi meters maintain their dominance as the preferred devices. Selecting the most accurate meter for wet gas flow presents a considerable challenge. However, a few significant observations can be made. Firstly, when precise measurements of both phases are required, the incorporation of a water cut meter alongside phase velocity measurement becomes imperative. For instance, the case of EMCO using only a Venturi meter resulted in a liquid flow accuracy relative to 10 %. Yet, the introduction of a water cut meter like KHRONE significantly improved liquid accuracy. Notably, enhancing accuracy in liquid flow measurement directly correlates with an improvement in gas flow accuracy. Certain commercial wet gas flow meters exhibit superior performance within the gas volume fraction (GVF) range of 98–100 % for liquid measurements (e.g., Weatherford and Emerson in Table 4). This phenomenon may be attributed to the transition from an annular regime to annular-mist or mist pattern at such high GVFs. In simpler terms, the concentration of the liquid film becomes exceedingly thin or even completely evaporates. This suggests that errors in liquid flow rate measurement arise primarily from the thin film thickness along the inner pipe wall. Another significant consideration relates to the reported optimal accuracy for gas flow rate, which hovers around 3 % for nearly all commercial wet gas meters. This limitation appears to stem from the inherent constraints in liquid flow rate accuracy, which, under the best circumstances, does not exceed 5 %.

The list of commercial wet gas meters is not limited to Table 4. There are additional wet gas meters introduced by companies, but they are not included in this table for brevity. For instance, KHRONE offers two other wet gas meters named WGS 1000 and WGS 2000, which are more cost-effective but less accurate compared to WGS 3000 [133]. WGS 1000 is presented as the most cost-effective model that utilizes a Venturi with a gas accuracy of ±5 % and water and condensate accuracy of not better than ±20 %. WGS 2000 uses PLR to determine liquid fraction with an accuracy of 3–5% for gas and ±10 % for liquid and condensate flows. The choice among these wet gas meters depends on the customer's preferences.

As for another example, AMETEK offers another wet gas meter named Dualstream 1, which utilizes a Venturi without any phase fraction meters [143]. Interestingly, excluding the water flow rate, this meter provides the same accuracy for gas and condensates mass flow rates compared to the advanced version (Dualstream 3). It uses the PLR together with gas to condensate ratio (CGR) to measure multi-phase flow of rates of gas, condensate and water in real time.

It is evident that Venturi tubes play a crucial role in measuring wet gas flow. However, to enhance the accuracy of the liquid phase, which can impact the accuracy of the gas phase, the use of a phase fraction meter is necessary.

6. Wet gas measurement in future

Expectations of the performance of a wet gas flowmeter vary noticeably. The spatial distribution of the liquid phase varies across

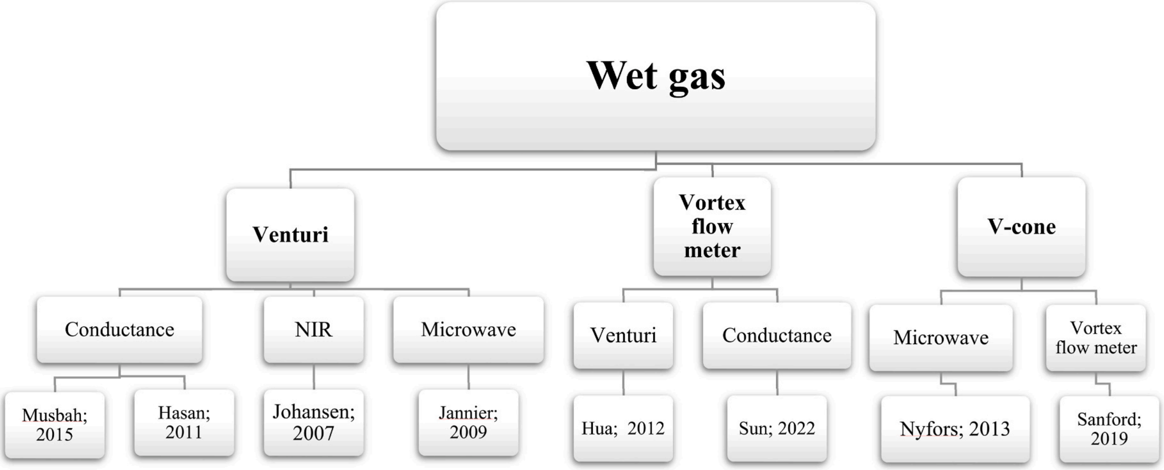


Fig. 21. Recent hybrid wet gas flow technologies.

these regions, in addition to differences in the liquid fraction. Therefore, it might be tricky to have a wet gas meter with the same uncertainty at all these regions, even though almost all end-users prefer to measure wet gas in the whole range. Although most end-users prefer a wet gas meter that can measure the entire range, it is important to note that single-phase flow meters alone may not achieve the desired level of certainty without the assistance of a liquid fraction meter. Some key aspects to consider for the future of wet gas measurement are as follows.

i. Advanced Metering Technologies: Continued research and development efforts will focus on enhancing metering technologies specifically designed for wet gas measurement. This includes the refinement of existing devices and the development of new technologies that can provide accurate and reliable measurements of wet gas flow rates.
ii. Improved Accuracy: Efforts will be directed towards improving the accuracy of wet gas flow rate measurements. This will involve the development of more physics-based correction algorithms, calibration techniques, and data processing methods to minimize errors and uncertainties associated with wet gas measurement.
iii. Multi-Phase Flow Measurement: As wet gas often consists of multiple phases such as gas, liquid, and condensates, future measurement techniques will aim to accurately quantify and differentiate these phases. This will enable a better understanding of the individual phase contributions and their impact on overall flow dynamics.
iv. Non-Intrusive Measurement: There is a growing interest in non-intrusive measurement techniques that do not require direct contact with the flowing media. These methods, such as acoustic, optical, impedance sensors, or electromagnetic-based sensors, offer the potential for accurate and non-disruptive wet gas flow measurement.
v. Integration of Advanced Data Analysis Techniques: The integration of advanced data analysis techniques, such as artificial intelligence, machine learning, and big data analytics, will play a significant role in improving wet gas measurement. These techniques can enhance data interpretation, pattern recognition, and anomaly detection, leading to more precise and reliable measurements.
vi. Industry Standards and Guidelines: The development of standardized procedures and guidelines for wet gas measurement will contribute to improved accuracy, consistency, and comparability of measurement results across different industries. This will facilitate better quality control and ensure reliable and consistent wet gas flow measurement practices.

7. Conclusion

This review seeks to enhance understanding of the challenges associated with measuring wet gas flows and provide insights into future developments. It attempts to utilize existing literature data to compare various devices, highlighting their advantages and disadvantages, with the ultimate goal of identifying the most effective solution for wet gas metering. Furthermore, hybrid methods in the literature were discussed as well as the industrial ones. Some points can be briefed as follow.

1) The definition of wet gas within the X_{LM} range up to 0.3, while disregarding or assuming an α_l of less than 10 %, is not true. Both experimental data and certain empirical models indicate that the actual wetness can be three times higher than the assumed value, reaching even more than 30 %. Consequently, relying only on X_{lm} for wet gas classification could lead to a significant misinterpretation of the flow conditions.
2) Among flow rate metering methods, it seems that more attention is toward Venturi, Cone meters, orifice, and fewer vortex flow meters. In addition, ultrasonic and Coriolis meters have shown major problems in wet gas flow. In the case of Coriolis, a stable signal in wet gas flow needs to be established. However recently drive gain shows a powerful and promising technique. There needs more research to verify the ability of drive gain or other internal parameters in the correction of Coriolis wet gas flow measurements. It is important to note that Coriolis meters measure the total mass flow, including both gas and liquid components, so a comparison using total mass rather than dry gas would be more appropriate.
3) Venturi and Cone meter are less intrusive to the flow of wet gas compared to the orifice. Both devices show a stable signal, good repeatability, and fair accuracy after correction, for both liquid and gas flow rates. Cone meter has a less sensitive response to liquid fluctuations than Venturi. Cone meter can be considered a priority if the liquid flow rate is not important. In contrast, it is a weakness for Cone meter if both phases should be measured especially in low liquid loading ($0.01<LVF<0.1$). Venturi seems to be slightly more robust (in terms of repeatability) and flexible (in terms of operating conditions).
4) Regardless of all models and corrections for Cone meter, Venturi and orifice to address the over-reading issue, it seems that their accuracy cannot be improved beyond the certain limits (in the best case-scenario, 3 % relative error for gas flow rate and 10 % for liquid flow rate). This limitation arises from the dependence of gas flow rate estimation on liquid fraction estimation in most correction

algorithms. Vortex flow meters have been suggested as a potential solution for this requirement.

5) Vortex flow meters have been relatively overlooked in the context of wet gas flow, particularly in industrial applications. However, this literature review highlights their potential for accurate wet gas measurement. Vortex flow meters exhibit robust signals and offer better accuracy for wet gas flow compared to other devices. However, their correction algorithms have not been as extensively developed as those for Venturi and Cone meters.
6) For liquid fraction meters, aside from radioactive methods, three methods have garnered more attention: microwave, conductance sensors, and NIR (Near-Infrared). Among these methods, conductance alone is limited to conductive materials and is not suitable for measuring three-phase flow void fraction, such as oil (condensate)/water/gas. Another approach involves using a combination of capacitance and conductance for three-phase flow. However, both microwave and NIR technologies have the potential to measure the fractions in the three-phase flow conditions. Nevertheless, in the case of NIR, there isn’t sufficient data available for multi-phase flow.

CRediT authorship contribution statement

Seyed Milad Salehi: Conceptualization, Writing - original draft, Writing - review & editing. **Liyun Lao:** Conceptualization, Supervision, Writing - review & editing. **Lanchang Xing:** Conceptualization, Writing - review & editing. **Nigel Simms:** Supervision, Writing - review & editing. **Wolfgang Drahm:** Funding acquisition, Supervision.

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.

Data availability

No data was used for the research described in the article.

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Nomenclature

English Symbols

A_T	Area of a DP flow meter throat (m^2)
C	Discharge coefficient of a DP flow meter
d	Width of a bluff body in a vortex flow meter (m)
D	Pipe diameter (m)
DP	Differential Pressure
DR	Density Ratio (−)
GVF	Gas Volume Fraction (−)
F	Bluff body frequency (s^{-1})
Fr	Froude number
I	Incident light intensity (−)
I_0	Transmitted light intensity (−)
l	Media thickness in Lambert-Beer law (cm)
$\dot{m}$	Mass flow rate (kg/hr)
LVF	Liquid Volume Fraction (−)
OR	Over-Reading in wet gas (−)
Q	Volumetric flow rate (m^3/hr)
Re	Reynolds number
R_{xy}	Cross-correlation function (−)
Sr	Strouhal number (−)
St	Stokes number (−)
S	Network parameter in the resonator sensors (dB)
T	The total time period for the cross-correlation method (s)
U	Flow velocity (m/s)
X_{LM}	Lockhart-Martinelli parameter (−)
$x(t)$	Upstream signal in the cross-correlation method (−)
$y(t)$	Downstream signal in the cross-correlation method (−)

Greek Symbols

ΔP	Differential pressure (Pa)
α	Void Fraction
β	Diameter ratio (−)
α_Δ	The absorption coefficient of light in Lambert-Beer law (cm^{-1})
λ	Wavelength (nm)
ε_r	Relative permittivity (−)
ε	Expansibility factor (−)
ρ	Density (kg/m^3)
ϕ_p	Droplet mass loading (−)

τ	Time lag for the cross-correlation method (s)

Subscripts

g	Gas
l	Liquid
m	Mixture
sg	Superficial gas
sl	Superficial liquid

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