Scientific Research Publishing

Journal of Flow Control, Measurement & Visualization, 2025, 12(1), 1-35
https://www.scirp.org/journal/jfcmv
ISSN Online: 2329-3330
ISSN Print: 2329-3322

Characterizing Trends in Metering Techniques for Wet Gas Measurement: A Critical Review

Ishigita Lucas Shunashu[1], Osmund Kaunde[2], Duncan Mwakipesile[3]

[1]Department of Mechanical and Industrial Engineering, College of Engineering and Technology, Mbeya University of Science and Technology, Mbeya, Tanzania
[2]College of Engineering and Technology, Mbeya University of Science and Technology, Mbeya, Tanzania
[3]Department of Innovations, Techno-Preneurship Acceleration Facility (ITAF), St. Joseph University of Science in Tanzania (SJUST), Dar es Salaam, Tanzania
Email: ishigitalc@gmail.com

How to cite this paper: Shunashu, I.L., Kaunde, O. and Mwakipesile, D. (2025) Characterizing Trends in Metering Techniques for Wet Gas Measurement: A Critical Review. *Journal of Flow Control, Measurement & Visualization*, **12**, 1-35.
https://doi.org/10.4236/jfcmv.2025.121001

Received: March 30, 2025
Accepted: July 11, 2025
Published: July 14, 2025

Abstract

This review critically examines advancements, performance, and challenges in wet gas measurement technologies, emphasizing the need for innovation and adaptation in industrial applications. Key advancements include the integration of machine learning (ML) for real-time calibration, hybrid metering systems combining differential pressure, ultrasonic, gamma-ray, and optical sensors, and the development of high-sensitivity hardware for diverse operational scenarios. Performance evaluations demonstrate promising accuracy by ML algorithms and hybrid systems for gas flow rates (<2%). Despite these successes, significant challenges persist, including dependency on flow regime-specific calibrations, noise interference, environmental sensitivity, and limitations in high gas and low liquid volume fractions. Besides, a lack of standardized testing and validation hampers the widespread adoption of these technologies. To address these gaps, this review recommends advancements in adaptive ML algorithms, robust and noise-resistant sensor designs, and extensive field validation across diverse conditions. The exploration of computational techniques, such as digital twins, alongside sustainability-focused designs, further highlights pathways for improvement. Through a detailed analysis of industry applications, this review assesses the suitability of existing methods while proposing a roadmap for future research to enhance measurement reliability, scalability, and adaptability in complex multiphase flow environments.

Keywords

Wet Gas Metering Technologies, Wet Gas Flow Meters, Metrology, Machine Learning, Multiphase Flow

1. Introduction

Wet gas measurement plays a vital role in the oil and gas, steam, and process industries, where accurate flow measurements are essential for effective production management, custody transfer, and regulatory compliance. The characterization of wet gas measurement depends on identifying the components to be measured, such as phase fraction, flow rate, liquid loading, and phase velocities, as well as the corresponding measurement methods. Wet gas flow, representing a two-phase mixture of gas and liquid, poses significant challenges to achieving precise flow measurements due to liquid loading [1]. Traditional single-phaser measurement methods, including differential pressure (DP) meters such as Venturi meters and Orifice plate meters, often encounter issues in handling multiphase flow and ultimately lead to over-reading and inaccuracies in measurement [2].

The focus on wet gas measurement began to gain prominence in the 1980s within the steam generation industry and subsequently attracted significant attention in both the oil and gas sectors, as well as in process industries, particularly in natural gas production. Accurate metering of wet gas flow is essential for estimating the actual gas flow rate and assessing the liquid loading within the gas-liquid mixture. A variety of methods and technologies for wet gas flow measurement have been developed and implemented, including Multiphase Flow Meters (MPFM), separation technology, and single-phase flow meters. Conversational Multiphase Flow Meters (MPFMs) come with substantial costs associated with investment, operation, and maintenance. The use of separation technology, which requires the installation of a liquid separator downstream from the dry gas flow meter alongside a liquid flow meter, is also expensive and involves cumbersome operations. In contrast, utilizing single-phase flow meters for wet gas metering offers an alternative approach.

This review paper investigates the capabilities of current wet gas metering technologies while highlighting the challenges and advancements that could support future developments. The specific objectives of this study include: i) identifying trends and advancements in wet gas metering techniques, ii) assessing the performance of various metering technologies for wet gas measurement, iii) analyzing the challenges and limitations of existing wet gas metering technologies, and proposing recommendations for addressing these issues, and iv) exploring the industry applications of available wet gas metering technologies and assessing the suitability of different methods for specific requirements.

The methodology employed in this work involves an extensive literature review, along with gap and performance analysis based on the reviewed data. This study is important for revealing the challenges and gaps in current wet gas metering methods and technologies while recommending areas for future research, attention, innovation, and exploration.

2. Wet Gas and Characteristics

2.1. Meaning of Wet Gas

There are different definitions of wet gas depending on the type of industry and its application. In the steam industry, separated steam is termed to be wet steam only when the steam quality x is greater than 0.5 [3]. In the oil and gas industry, wet gas was first referred to as the hydrocarbon mixture with a gas volume fraction (GVF) greater than 90% [4]. However, in the process industry and ongoing research, wet gas is reported as the gas-liquid two-phase flow having Lockhart-Martinelli (L-M) X_{LM} parameter of 0.35 or 0.3. This includes the early research by Shell that concluded that a wet gas is defined by $X_{LM} \le 0.35$ as from the experimental data, which also reported that slugging in the pipe can become significant at $X_{LM} > 0.35$. In a recent study by Hall *et al.* [3], wet gas is defined using the Lockhart-Martinelli parameter as a gas-liquid two-phase flow having $X_{LM} < 0.3$. This definition is recognized by ISO/TR 12748 [5] and supported by industry groups, including the Norwegian Society for the Oil and Gas Measurement (NSOGM) [6], the American Petroleum Institute (API) [3], and the American Society of Mechanical Engineers (ASME) [7]. According to Hall *et al.* [3], the lack of standardized terminology and measurement techniques has led to inconsistencies in the field.

In the natural gas production industry, wet gas is formed when liquid is present in the flowing gas, which occurs due to the condensation of water vapour in the gas as a result of drops in pressure and temperature. However, the presence of liquid in natural gas can also be attributed to changes in well conditions (such as retrograded and injected condensates), the inherently wet nature of certain gas fields (particularly in offshore natural gas production), and various other factors that may lead to liquid formation in natural gas. As a result, natural gas condensate is typically found in the form of wet gas throughout the exploration, production, and transmission stages.

2.2. Characteristics of Wet Gas

Wet gas flow is characterized by a gas phase with small amounts of liquid, typically quantified using the Lockhart-Martinelli parameter. Several interrelated parameters derived from the Lockhart-Martinelli parameter (X_{LM}) include the gas volume fraction (GVF), liquid volume fraction (LVF), and flow quality (expressed as liquid-to-gas volume ratio and liquid-to-gas mass flow rate ratio). The density ratio (DR) serves as the independent variable for all five parameters, as the expression cannot be equated without incorporating a function of DR. These five parameters that characterize wet gas are illustrated in **Figure 1** and correspond to Equation (1).

$$X_{LM} = \frac{\dot{m}_l}{\dot{m}_g}\sqrt{\frac{\rho_g}{\rho_l}} = \frac{1-\text{GVF}}{\text{GVF}}\sqrt{\frac{\rho_l}{\rho_g}} = \frac{1-x}{x}\sqrt{\frac{\rho_l}{\rho_g}} = \frac{\text{LVF}}{1-\text{LVF}}\sqrt{\frac{\rho_l}{\rho_g}} = \frac{Q_l}{Q_g}\cdot\frac{\rho_l}{\rho_g} \tag{1}$$

where X_{LM} denotes Lockhart Martinelli parameter, $\dot{m}_l$ and $\dot{m}_g$ are liquid and gas mass flow rate, ρ_g and ρ_l are liquid and gas density, Q_g and Q_l gas and liquid flow rate, x represent gas quality.

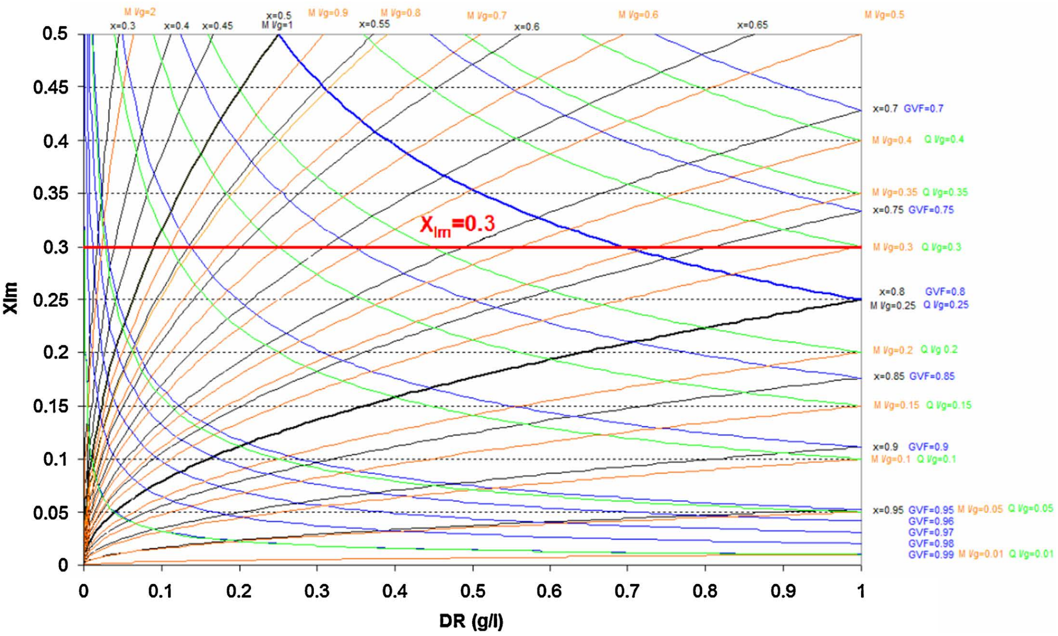

Figure 1. Five parameters, relationships, and comparison expressing wet gas [3].

3. Wet Gas Measurement

3.1. Wet Gas Flow Measurement Overview

The multiple parameters in the wet gas are determined using a specialized multiphase flow meter or a step-by-step separation process for the liquid and gas before ascertaining each phase's measurement components. Since wet gas measurement can be influenced by process conditions, flow rates, and all fluid physical properties (pressure, temperature, composition, phase envelope, energy content, etc.), appropriate techniques should be applied to ensure optimised production and fair transactions in the transmission or custody transfer. The four existing wet gas measurement techniques include: (i) installation of a single-phase flow meter upstream of the gas-liquid separators [8] [9] as presented in **Figure 2** (ii) the use of a multiphase flow meter (MPFM) [9] [10] as illustrated in **Figure 3** below (ii) the use of a single-phase flowmeter (with derived correlation to rectify the over-reading error caused by liquid loading in the flowing gas) [11]-[13] which is depicted in **Figure 4** below, as well as (iv) the phase fraction detection or tomography method as investigated by various researchers like [14]-[16].

Wet gas measurement using conventional two-phase liquid-gas separators or three-phase separators upstream of the flow meters is inherently bulk, involving high installation costs and considerable maintenance. Moreover, multiphase flowmeters (MPFM) are subject to very high investment and maintenance costs, are flow regime dependent (homogeneous, stratified, or annular), and require tedious calibration. Due to their complexity and multisystem nature, MPFM may encounter pressure drops due to flow interference, and some have internal moving parts that reduce reliability, thereby increasing maintenance costs and complicating operations in piggable pipelines, as stipulated by [17].

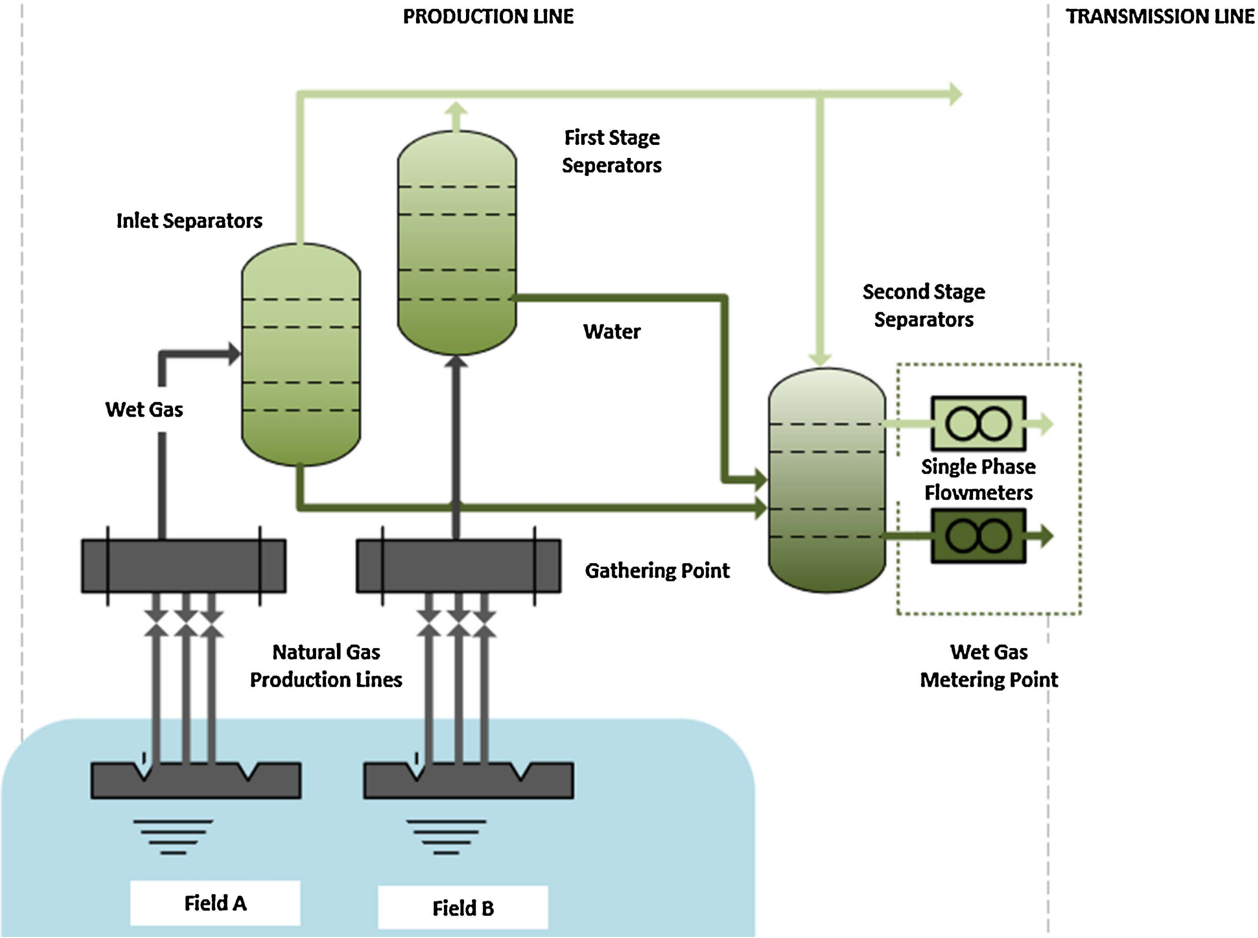

Figure 2. Separator system in wet gas measurement.

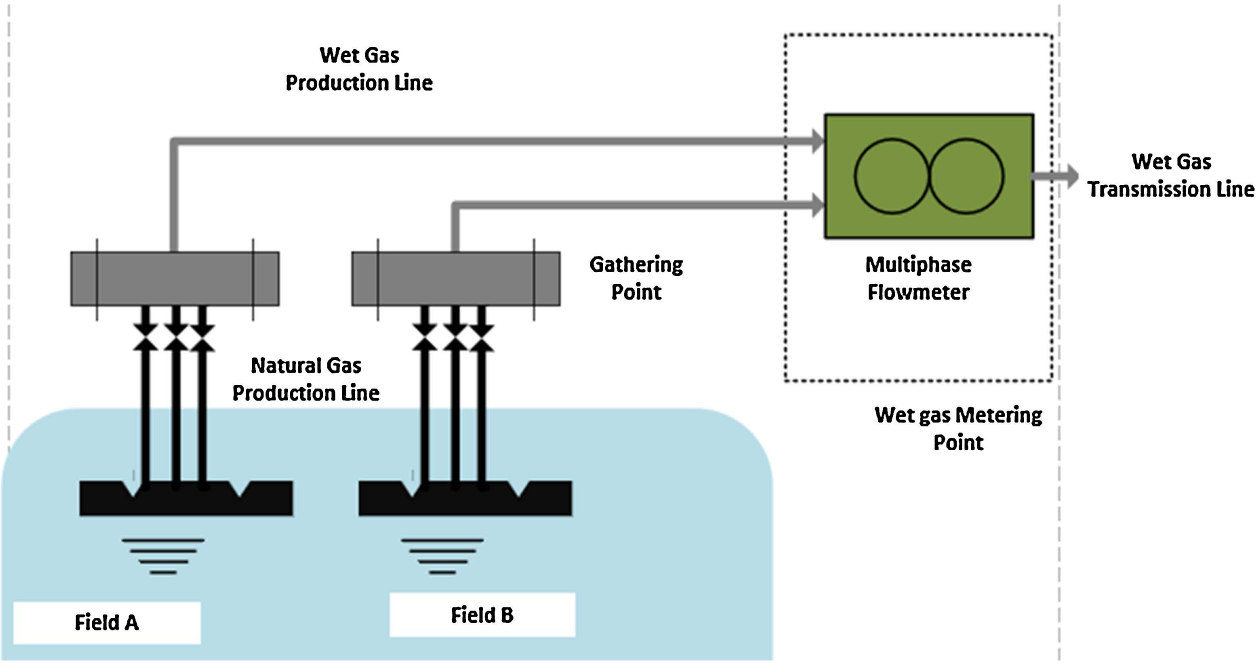

Figure 3. Multiphase flowmeter in wet gas measurement.

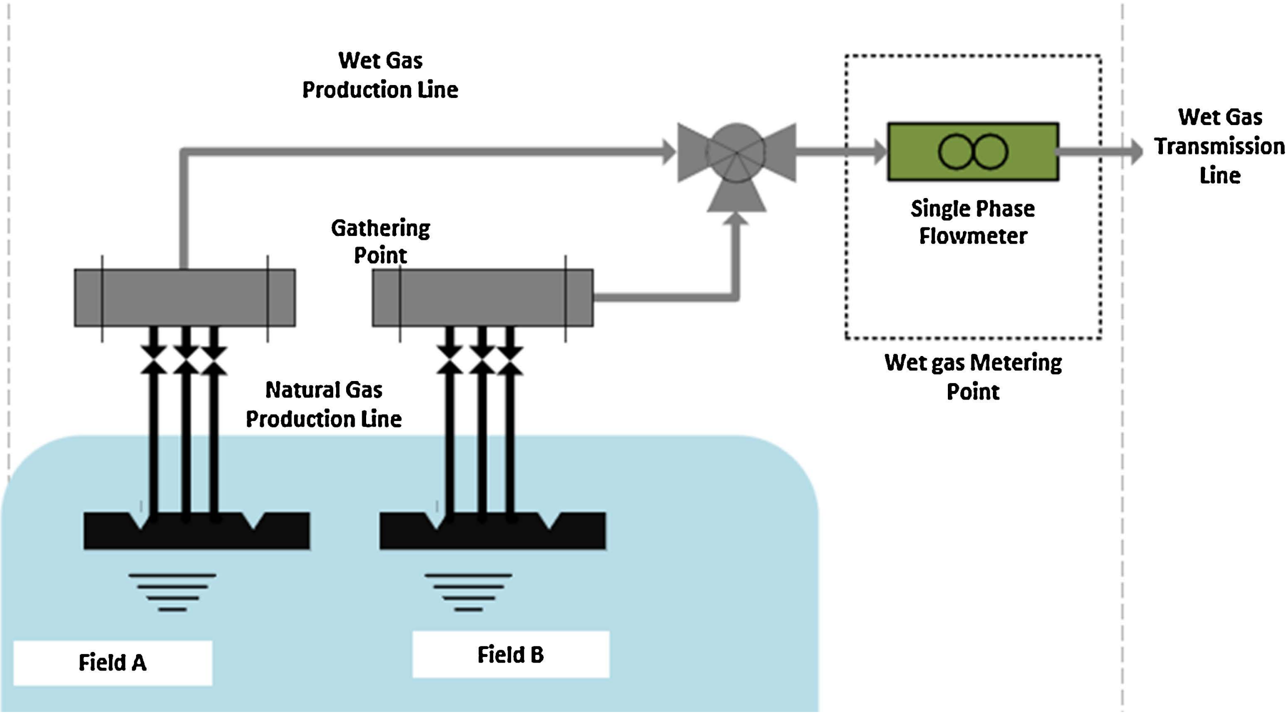

Figure 4. Single-phase flowmeter in wet-gas measurement.

3.2. Challenges of Environmental Variation to Existing Traditional Technologies

Generally, the existing wet gas metering technologies, such as Multiphase Flow Meters (MPFMs) and Differential Pressure (DP) meters, employ various strategies to handle environmental variations like temperature, pressure, and salinity. MPFMs typically use phase fraction sensors and flow models to compensate for changes in fluid properties, while DP meters rely on correlation-based corrections to adjust for wetness-induced over-reading as discussed in section 4.1 of this paper. However, these technologies face challenges in extreme conditions. For instance, DP meters often exhibit positive bias in wet gas flows due to liquid presence, leading to inaccurate gas flow rate readings. Additionally, MPFMs may struggle with salinity variations, which alter dielectric properties and affect phase fraction measurements. Another gap is the limited adaptability of these meters to dynamic flow regimes, requiring frequent recalibration.

4. Classification of Single-Phase Wet Gas Metering Technologies

Measurement of wet gas using a single-phase flow meter remains a persistent challenge in field operations. Many existing methods are invasive and intrusive, which restricts their application under extreme pressure and temperature conditions. Consequently, there is a pressing need to improve the accuracy of wet gas flow measurement, particularly by enhancing over-reading (OR) correlation models. These challenges in wet gas measurement for the oil and gas industry and the petrochemical industry have led to innovations where various metering techniques have been studied and applied massively to improve the accuracy of wet gas flow rate measurement. **Figure 5** illustrates the classification of various metering technologies for wet gas measurement that currently exist in industry.

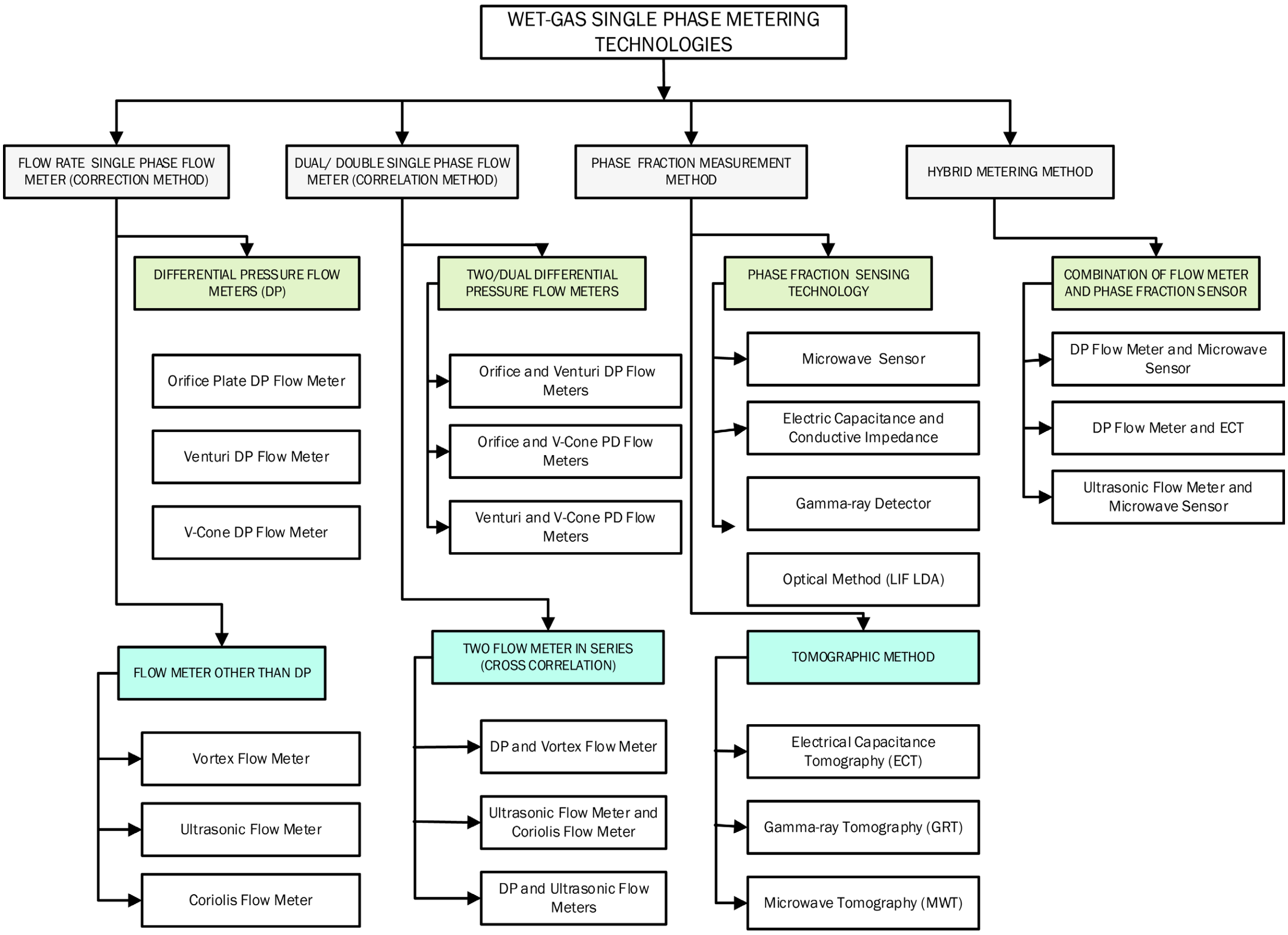

Figure 5. Classification of single-phase wet gas metering techniques.

4.1. Differential Pressure (DP) Flow Meters

Differential Pressure (DP) flow meters, such as the orifice plate, venturi tube, and v-cone, are among the most widely used single-phase metering systems for wet gas measurement. These devices have been extensively studied and have remained a focal point of research since the 1960s. To accurately measure the actual mass flow rate using DP flow meters, specialized correlation models have been developed to address "metering over-reading," which arises due to the presence of the liquid phase [12] [18].

The fundamental operating principle of DP flow meters is based on the obstruction principle. As the fluid flows through the metering section, an obstruction (such as an orifice plate or venturi nozzle) creates a pressure drop. This pressure drop is directly proportional to the flow rate within the pipe [19] [20]. According to ISO5167 [19] [20], DP meters are classified based on the structure of their primary elements, including orifice plates, pitot tubes, cone meters, nozzles, and venturi meters. Each of these designs offers unique advantages, making DP meters versatile tools in wet gas measurement. The fundamental equation of the DP flow meter is expressed in Equation (2) below.

$$Q_v = \frac{C_d A_2}{\sqrt{1-\beta^4}} \cdot \sqrt{\frac{2g(\Delta P)}{\rho}} \tag{2}$$

where Q_v is the volumetric flow rate, C_d is the discharge coefficient of the DP element, A_2 is the cross-sectional area of the DP element, ΔP is the differential pressure, ρ is the density of wet gas, β is the diameter ratio d/D or A_1/A_2, and g is the gravitational constant.

Differential pressure (DP) flowmeters are versatile devices utilized for both liquid and gas metering in various industrial applications. Orifice meters, a type of DP flowmeter, play a critical role in numerous process industries where they are used to measure gas, liquid, or even gas-liquid two-phase flows. In the energy sector, orifice meters serve as reference instruments for natural gas custody transfer due to their reliability. According to Upp & LaNasa [21], the accuracy of DP meters in measuring actual gas flow ranges from ±0.5% to ±2%. However, when measuring wet gas flows, the presence of liquids requires the application of an over-reading (OR) correlation, which acts as a correction factor when combined with analytical equations. The precision of wet gas flow measurements heavily relies on the accuracy of the selected over-reading correlation model.

Over-reading correction (OR), also referred to as wet gas correction (WGC) models, is indispensable for single-phase flow meters in accurately estimating the actual flow rate of wet gas. This involves correcting the overestimation caused by the presence of liquid in the flow. These models integrate fundamental flow principles with empirical or experimental data derived from wet gas test loops. The concept of over-reading in wet gas flow is defined as the ratio between the measured gas mass flow rate and the actual gas mass flow rate. This critical relationship serves as the foundation for applying OR models effectively to achieve precise and reliable wet gas measurements. Equation (3) expresses the empirical formula for over-reading correction (OR), where Q_{tp} represents wet gas flow rate and Q_g denotes the actual gas flow rate.

$$OR = \frac{Q_{tp}}{Q_g} \tag{3}$$

Extensive research has been conducted on wet gas measurement using single-phase flow meters combined with correlation models, particularly in differential pressure (DP) techniques. Notable work includes Murdock's hypothesis [22] on separated liquid-gas two-phase flow patterns, which led to a semi-empirical correlation based on experimental data using orifice plate differential flow meters. Similarly, Chisholm [23] [24] developed a wet gas correlation model for orifice plates, rooted in the momentum conservation equation for gas-liquid two-phase systems.

Further contributions include the Lin correlation [25], the De Leeuw correlation

[26], and the Smith & Leang model [27], which introduced the concept of a "blockage factor" for orifice plates and Venturi meters. Comparative analyses of these DP sensor correlation models have been carried out using experimental data, revealing that the Venturi meter demonstrates superior performance in wet gas measurement applications [25]-[27]. Research by Lide *et al.* [18] established the Venturi sensor as a particularly effective option for such measurements. Detailed equations for differential pressure over-reading models, along with their performance metrics and limitations, are summarized in the accompanying **Table 1** below.

Table 1. Over-reading correlation models for DF flow meters.

s/n	Model	Concept	Parameters	Performance	Model equation
1	Homogeneous Model [31]	Based on the Orifice & venturi tube on a pseudo-single-phase. Homogeneous density ρ_{Hom} determined based on ρ_l and ρ_g. $\rho_{Hom} = \frac{\rho_l \rho_g}{\rho_l x + \rho_g (1-x)}$	Lockhart-Martinelli parameter X_{LM}	±3% uncertainty	$OR = \sqrt{1 + C_{Hom} X_{LM}}$
2	Murdock Model (1962)	Used both Orifice and Venturi. Based on data from the two-phase flow using steam-water, air-water, and natural gas-water.	Density Ratio $\frac{\rho_l}{\rho_g}$ Lockhart-Martinelli parameter X_{LM}	±1.5% uncertainty at 95 confidence level & $k = 2$	$OR = 1 + 1.26 X_{LM}$
3	Lin Model	Based on the Orifice flowmeter. Investigated the interaction at the interphase level Defined variable coefficient Q_v.	Volumetric flow rate Q_v Lockhart Martinelli parameter X_{LM}	±0.5% uncertainty at a beta ratio between 0.5 and 0.7.	$OR = 1 + Q_v X_{LM}$
4	Chisholm Model	Based on the Orifice Plate. Investigate the effect of the differential pressure value independent of X_{ML}.	Density Ratio $\frac{\rho_l}{\rho_g}$ Lockhart-Martinelli parameter X_{LM}	±2% uncertainty in natural gas	$OR = \sqrt{1 + \left[\left(\frac{\rho_l}{\rho_g}\right)^{\frac{1}{4}} + \left(\frac{\rho_g}{\rho_l}\right)^{\frac{1}{4}}\right] X_{LM} + X_{LM}^2}$ $OR = \sqrt{1 + C_{Chi} X_{LM} + X_{LM}^2}$
5	De Leeuw Model	Based on the Venturi tube in wet gas in horizontal flow. Correlation of the dependence of the Froude number was also observed. Investigated the model using nitrogen gas and diesel to develop a two-phase flow.	Lockhart-Martinelli Froude Number Fr_g Density Ratio $\frac{\rho_l}{\rho_g}$	±2% uncertainty	$OR = \sqrt{1 + C_{dL} X_{LM} + X_{LM}^2}$ $Fr_g \geq 1.5 : n = 0.606\left(1 - \mathrm{e}^{-0.746 Fr_g}\right)$ $0.5 < Fr_g < 1.5 : n = 0.41$
6	Smith and Leang Model	Used both Orifice and Venturi to account for mass fraction $(1-x)$. Investigated the decrease in cross-sectional area due to blockage of the orifice section caused by the presence of liquid.	Gas Mass Fraction (GMF) x	±2% uncertainty at 95 confidence level & $k = 2$	$OR = \frac{1}{BF}$ $BF = 0.637 + 0.421(1-x) - \frac{0.00183}{(1-x)^2}$

Despite being widely used for wet gas flow measurement due to their high reliability, availability of correlation models, and low cost [28], DP-type flow sensors exhibit several limitations. These include flow pressure drop and swirl/eddy formation caused by their intrusive nature, which disturbs flow fields and increases measurement uncertainty, making them unsuitable for placement upstream of other components [17] [29]. Their integration with radioactive gamma-rays for density and composition measurement raises health and safety concerns [17]. Additionally, DP sensors struggle to accurately capture phase distribution, including void fraction and film thickness [30], and over-reading correction models often lack experimental validation [30]. Moreover, obtaining the initial liquid flow rate required for gas phase flow rate calculation is practically impossible in industrial applications [13].

Recent advancements in wet gas measurement based on DP single-phase flowmeters have established the foundation for integrated dual-DP metering systems and hybrid metering systems to improve accuracy and reliability. Key developments include the application of double differential pressure (DP) sensor technologies, such as double Venturi sensors, Venturi and V-cone combinations [32], standard and slotted orifices [33], V-cone paired with shuttle-cone [34], and double V-cone flowmeters [35]. Furthermore, dual sensor configurations have emerged, integrating DP flow sensors with additional technologies, such as Venturi combined with vortex meters [34].

Hybrid metering systems have also advanced significantly, merging flow sensors with phase fraction sensing technologies. Examples include Venturi, orifice plates, V-cones, or turbines paired with resistive void fraction sensors [32] [36]. Venturi meters integrated with Electrical Capacitance Tomography (ECT) or Electrical Resistance Tomography (ERT) sensors and V-cone or Venturi meters combined with microwave probes [37] [38]. These innovations are designed to address the challenges of wet gas metering while enhancing measurement accuracy in diverse operational settings. **Table 2** below presents the gap analysis on differential pressure (DP) metering technology in wet gas measurement.

4.2. Ultrasonic Flow Meter (USM)

An ultrasonic flow meter (USM) is a non-invasive and non-intrusive device specifically designed to measure single-phase fluid flow. When using a USM for wet gas flow measurement, it is essential to determine the over-reading correction factor (OR) to achieve accurate flow rate readings. Numerous studies have explored the application of ultrasonic flow meters in wet gas flow measurement, along with the development of an over-reading correction factor for flow rate accuracy.

Numerous studies, such as those by Xing *et al.* [28], explored non-intrusive single-phase ultrasonic metering (USM) approaches, particularly in stratified and annular gas-liquid flow scenarios, using void fraction models for validation. These methods have been tested in controlled environments with different flow patterns and conditions, such as horizontal pipelines under varying pressures and velocities.

Table 2. Gap analysis of DP flow meters for wet gas measurement.

Aimed Knowledge	Gap Identification	Desired Outcome	Reference
Accurate modeling of wet gas flows	Correlation models rely heavily on empirical data and lack adaptability to complex flow conditions	Development of advanced, adaptive models that account for real-time changes in flow patterns	[22]-[24]
Improved accuracy in high liquid volume fractions	DP sensors exhibit over-reading and high uncertainty in wet gas flows with high liquid content	Refined correction models and improved calibration techniques to mitigate over-reading errors	[18] [30]
Comprehensive phase distribution measurements	Struggles with capturing phase distributions (e.g., void fraction and film thickness)	Integration of advanced sensors or hybrid technologies for precise phase measurement	[30]
Minimizing flow disturbances	Intrusive DP sensors cause pressure drops and swirl/eddy formations, disrupting flow fields	Development of non-intrusive DP sensors or designs that minimize flow disturbance	[17] [29]
Safe and efficient wet gas metering	Radioactive gamma-ray integration raises health and safety concerns	Exploration of alternative, non-radioactive sensor technologies	[17]
Reliable performance in industrial applications	Inability to measure the initial liquid flow rate accurately in real-world industrial setups	Innovative techniques or technologies capable of addressing practical limitations in obtaining critical flow rate parameters	[17]
Experimentally validated over-reading correction models	Many correction models lack experimental validation, reducing reliability	Conduct rigorous experimental studies to validate and refine over-reading correction models	[30]

Similarly, van Putten *et al.* [2] advanced the understanding of ultrasonic methods by developing an over-reading correction model for stratified and dispersed flows, leveraging dimensionless parameters like Lockhart-Martinelli numbers and Froude numbers. Further investigations by Xu *et al.* [30] emphasized void fraction and liquid film thickness as primary contributors to over-reading in ultrasonic meters, proposing a model based on liquid film estimation. Additionally, hybrid approaches, like the work of Gysling *et al.* [39], integrated DP meters with sonar-based flowmeters to achieve improved accuracy, while Funck & Baldwin [40] validated ultrasonic methods using clamp-on and traditional configurations in wet gas conditions.

The equation of flow by TT-USM is expressed in Equation (4) below. Where; denotes wet gas volumetric flow rate, θ represents propagation angle, L indicates the distance between transducers, t_2 and t_1 represents the time of flight of ultrasonic pulse from upstream to downstream transducers, respectively.

$$Q = A \cdot \frac{L}{2\cos\theta}\left(\frac{t_2 - t_1}{t_2 t_1}\right) \tag{4}$$

The performance of the USM metering technique for wet gas flow is highly influenced by flow conditions and the specific measurement techniques employed. Xing *et al.* [28] identified errors in gas flow rate predictions ranging from 3.7% to 19.0%, with the Lockhart-Martinelli model demonstrating superior accuracy under stratified flow conditions. Similarly, Van Putten *et al.* [2] reported an uncertainty level below 4% using a dimensionless correction algorithm tailored for wet gas flows. In another research by Xu *et al.* [30], USM achieved prediction errors within ±15%, with 88% of the data points falling within a ±5% margin, emphasizing the effectiveness of ultrasonic meters when calibrated for variables such as void fraction and liquid film thickness [30]. Gysling *et al.* [39] demonstrated an accuracy of ±2% for gas flow rates and ±10% for liquid flow rates through the integration of differential pressure and sonar-based meters. Furthermore, FLEXIM clamp-on ultrasonic meters tested in [40] achieved errors under 8% across varying pressure conditions, while [41] highlighted the reliability of ultrasonic meters in stratified flows but noted significant performance degradation under mist flow conditions.

Despite the promising results, ultrasonic flow meters face several limitations and challenges. For example, Xing *et al.* [28] identified the reduction of gas flow paths due to liquid presence as a key source of error, while Xu *et al.* [30] highlighted the reliance on assumptions like pre-known liquid flow rates, which may not be practical in field applications. Funck & Baldwin [40] noted issues with liquid accumulation in pipes, leading to signal loss in high turbulence or near valves [42]. In addition, signal attenuation, pressure dependency, and ultrasonic energy loss at high gas volume fractions (GVFs) pose significant obstacles, as observed by Meribout *et al.* [43]. To address these challenges, researchers like Chang & Morala [44] suggested extending correlation models to include high viscosity effects, while recent advancements such as Contra-Propagated Transmission Ultrasonic Techniques [45] attempt to refine two-phase flow characterization. They suggested more innovations, such as enhancing signal processing techniques and also integrating hybrid systems, which could combine the strengths of various metering technologies to mitigate limitations. **Table 3** below summarizes the gap analysis based on the existing studies for the USM metering method in wet gas flow measurement.

4.3. Coriolis Flow Meters

Coriolis flow meters are widely used for mass flow measurement due to their ability to directly measure mass flow rates and density. In multiphase flow, including wet gas, the methods often involve modifications to standard Coriolis technology to account for the presence of multiple phases. The fundamental equation of the Coriolis flow meter is expressed in Equation (5) below.

Where q_m is the mass flow rate, F_c is the Coriolis force, ω is the angular velocity of the tube, d is the length of the tube, and the c constant induced as a correction of tube bending.

$$q_m = \frac{F_c}{2 \cdot c \cdot \omega \cdot d} \tag{5}$$

The use of Coriolis flow meters in wet gas measurement has been investigated in various research. Weinstein *et al.* [46] highlighted that Coriolis meters operate by measuring the oscillation of flow tubes, which can be disrupted by gas-liquid interactions [46]. Advanced signal processing techniques have been developed

Table 3. Gap analysis of ultrasonic flow meters for wet gas measurement.

Aimed Knowledge	Gap Identification	Desired Outcome	Reference
Accurate measurement in stratified and annular flows	High errors (3.7% - 19%) in gas flow rate predictions due to liquid film impact and complex flow conditions	Development of advanced correction models calibrated for stratified and annular flow regimes	[28] [30]
Accurate over-reading correction models	Over-reading due to void fraction and liquid film thickness; inadequate real-time adjustments in dispersed flows	Real-time adaptive algorithms for liquid film estimation and void fraction measurements	[2] [30]
Reliable signal transmission in turbulent flows	Liquid accumulation and high turbulence near valves cause signal loss	Improved ultrasonic sensor designs or hybrid meters with better turbulence resistance	[40] [43]
Minimized energy losses at high gas volume fractions	Ultrasonic energy attenuation and pressure dependency at high gas volume fractions	Use of novel techniques like Contra-Propagated Transmission Ultrasonic Methods to enhance energy efficiency	[43] [45]
Applicability in industrial settings	Assumes pre-known liquid flow rates, impractical in real-world applications	Development of field-ready adaptive models capable of estimating liquid flow rates under varying conditions	[30]
Versatility under varying viscosity conditions	Existing models fail to include viscosity effects	Expansion of ultrasonic models to incorporate high-viscosity flow scenarios	[44]
Integration with other metering technologies	Limitations of single-phase measurement techniques	Development of hybrid systems combining ultrasonic, DP, and sonar-based technologies for enhanced multiphase measurement	[39]

to mitigate these disruptions and improve accuracy. Li & Henry [47] introduced an algorithm to remediate errors caused by two-phase conditions, focusing on drive gain adjustments to maintain tube vibration. Likewise, Xu *et al.* [30] explored the use of Coriolis meters in stratified and annular flows, emphasizing the importance of calibrating for void fraction and liquid film thickness [30].

The performance of Coriolis meters in wet gas conditions varies depending on the flow regime and calibration. Weinstein *et al.* [46] reported that errors in multiphase conditions are primarily due to decoupling effects, where gas bubbles or liquid droplets move independently of the oscillating flow tubes. Li & Henry [47] demonstrated that with advanced algorithms, Coriolis meters could achieve an uncertainty of ±1.5% - 2% for gas flow rates in wet gas conditions. However, it was noted that the accuracy of Coriolis meters decreases with increasing gas volume fractions (GVF), with errors reaching up to ±15% in extreme cases [30].

Coriolis flow meters are extensively used in the oil and gas industry for applications such as wellhead monitoring, custody transfer, and process optimization. Weinstein *et al.* [46] highlighted their use in upstream allocation and net oil measurement, where accurate mass flow rates are critical. Li & Henry [47] also demonstrated their application in wet gas pipelines, where the meters were able to detect liquid fractions as low as 0.013% by volume [47]. Besides, the suitability of Coriolis flow meters for stratified and annular flow patterns was verified, making them valuable for multiphase flow measurement in pipelines [30].

Despite their advantages, Coriolis meters face several limitations in wet gas measurement. Weinstein *et al.* [46] identified decoupling effects as a major source of error, particularly in high GVF conditions. Li & Henry [47] noted that signal attenuation and noise due to turbulence and liquid slugs can significantly affect measurement accuracy. Likewise, Xu *et al.* [30] pointed out that the assumption of known liquid flow rates in calibration models is often impractical in real-world applications. Moreover, the high cost of Coriolis meters and their sensitivity to installation conditions pose challenges for widespread adoption [30].

To address these challenges, researchers have proposed several improvements. Weinstein *et al.* [46] recommended optimizing installation practices and using advanced signal processing to reduce errors. Li & Henry [47] suggested the development of more robust algorithms to handle two-phase conditions and improve accuracy [48]. Furthermore, the need for better calibration models that account for varying flow regimes and liquid fractions was emphasized [30]. Future research could focus on integrating Coriolis meters with hybrid systems to leverage the strengths of multiple measurement technologies [30]. **Table 4** below summarizes the gap analysis based on the existing Coriolis metering technology in wet gas flow measurement.

4.4. Dual Flow Meters

Dual differential pressure (DP) flow meters use two pressure sensors in series to measure wet gas flow rates. This involves tracking pressure drops across flow

Table 4. Gap analysis of Coriolis (mass) flow meters for wet gas measurement.

Aimed Knowledge	Gap Identification	Desired Outcome	Reference
Accurate oscillation measurements in multiphase flows	Disruptions due to decoupling effects caused by independent gas bubbles or liquid droplets	Development of advanced signal processing techniques to minimize oscillation disruptions	[46]
Improved calibration for complex flow regimes	Calibration models assume pre-known liquid flow rates, which is impractical in industrial applications	Adaptive real-time calibration methods for varying flow regimes and liquid fractions	[30]
Enhanced accuracy in high GVF conditions	Accuracy decreases with increasing gas volume fractions; errors reach up to ±15% in extreme cases	Refined algorithms to handle high GVF conditions and improve overall accuracy	[30] [47]
Reliable signal transmission in turbulent flows	Noise and signal attenuation due to turbulence and liquid slugs affect accuracy	More robust algorithms and sensor designs to mitigate noise and turbulence	[46] [47]
Versatility in wet gas applications	Limitations in detecting and quantifying low liquid fractions in stratified and annular flows	Hybrid systems or improved sensors capable of detecting and quantifying low liquid fractions	[30] [47]
Cost-effective and scalable solutions	High cost and sensitivity to installation conditions reduce widespread adoption	Exploration of cost-effective designs and improved installation practices	[46]
Integration with hybrid systems	Single-method limitations reduce overall reliability and adaptability	Integration of Coriolis meters with DP and ultrasonic technologies to leverage the strengths of multiple systems	[30]

like Venturi meters or orifice plates. Methods vary: Xu *et al.* [32] combined a Venturi and a V-Cone meter, correlating pressure drops with flow rates using empirical models, while Agar and Farchy [49] paired Venturi meters with sonar sensors for improved precision in wet gas conditions. Other dual DP methods involved standard orifices and slotted orifices [33], V-cone plus shuttle-cone [34]. However, Xu *et al.* [32] reported uncertainties of ±2% for gas and ±10% for liquid flow rates under controlled conditions. Agar and Farchy [49] reduced gas flow rate uncertainty to below ±5% by integrating sonar sensors. Despite these innovations, limitations persist. High LVF conditions impair accuracy, liquid slugs disrupt measurements, and calibration demands extensive data. Dual DP systems also increase costs and require maintenance, with empirical models limiting adaptability to diverse flow scenarios. Researchers suggest solutions such as adaptive calibration, advanced sensors like gamma-ray and microwave for better phase measurements, and machine learning to reduce reliance on empirical models [32] [34].

Dual flow meters other than DP have also been investigated in various research. Xing *et al.* [29] studied a novel method for measuring gas-liquid two-phase flows with low liquid loading, combining ultrasonic flowmeters (USF) and Coriolis mass flowmeters (CMF). A coupling model is developed by integrating these measurements, allowing for the estimation of gas and liquid mass flow rates. Experimental validation in stratified and annular flow regimes demonstrated root-mean-square errors (RMSE) of 3.09% for gas mass flow rate and 12.78% for liquid mass flow rate under specific pressure and flow conditions. Despite its promise, the method faces limitations, including measurement errors caused by complex flow regimes, noise interference, and liquid film effects. The CMF's accuracy decreases with increasing compressibility and asymmetry in two-phase flows, while the USF struggles with variable velocity profiles and interfaces. Suggested improvements include advanced signal processing, adaptive algorithms for void fraction and flow regime detection, and further experimental validation [29]. **Table 5** below summarizes the gap analysis for the existing studies for the dual DP metering method in wet gas flow measurement.

4.5. Cross Correlation Method

Cross-correlation is another metering method that has been used in wet gas flow measurement. Cross-correlation techniques involve placing two flow meters in series along a pipeline to measure the tagged signals between the two sensors. This method is widely used for velocity and flow rate estimation in multiphase flows. Munir and Khalil [51] underscored the use of ultrasonic, capacitive, and electrostatic sensors in cross-correlation systems to track flow dynamics in gas-liquid mixtures. The technique relies on signal processing to correlate the time delay between the upstream and downstream sensors, enabling the calculation of flow velocity. Muhamedsalih and Lucas [52] implemented impedance-based cross-correlation flow meters, using electrode arrays to measure local solids volume fractions and velocities in multiphase flows. Tomaszewska-Wach *et al.*, [50] also examined the application

Table 5. Gap analysis of dual flow meters for wet gas measurement.

Aimed Knowledge	Gap Identification	Desired Outcome	Reference
Accurate measurements of wet gas flow rates	High LVF conditions impair accuracy, and liquid slugs disrupt pressure measurements	Development of adaptive calibration techniques and real-time liquid slug mitigation strategies	[32] [49]
Integration of dual DP meters with advanced sensors	Empirical models limit adaptability to diverse flow scenarios	Incorporation of advanced sensors like gamma-ray and microwave technologies for better phase measurements	[32] [34]
Cost-efficient and scalable dual DP systems	Increased system costs and maintenance requirements due to complex calibration and additional sensors	Research into cost-effective designs and maintenance-free calibration systems	[49] [50]
Accurate coupling of multiple flow meter technologies	Measurement errors caused by noise interference, liquid film effects, and flow asymmetry in dual USF-CMF configurations	Advanced signal processing and hybrid flow coupling models to address noise and liquid film challenges	[29]
Reliable performance in stratified and annular flows	Variable velocity profiles and interfaces in ultrasonic flowmeters reduce accuracy under stratified and annular flow regimes	Enhanced algorithms and further experimental validation for stratified and annular flow performance	[29]

of standard and slotted orifice plates for wet gas flow metering and explored the effects of orifice geometry on measurement accuracy [50]. Results showed that slotted orifices generate lower differential pressures compared to the standard orifice, which improves pressure recovery but reduces metering sensitivity [50]. Likewise, Monnet *et al.* [53] demonstrated the use of cross-correlation in multiphase meters for well testing, combining differential pressure and velocity measurements to improve accuracy in wet gas conditions.

The performance of cross-correlation methods depends on sensor configuration, flow conditions, and signal processing algorithms. Munir and Khalil [51] reported that cross-correlation systems achieve velocity measurement uncertainties of ±2% - 5% in controlled laboratory conditions [51]. Muhamedsalih and Lucas [52] demonstrated that impedance-based systems could achieve flow rate uncertainties below ±4% for solids-water mixtures, with similar potential for wet gas applications. Monnet *et al.* [53] noted that combining cross-correlation with other metering techniques, such as differential pressure, reduced overall uncertainty to ±2% for gas flow rates and ±10% for liquid flow rates in wet gas scenarios. These techniques were widely applied in industries such as oil and gas, chemical processing, power generation, and pipelines transporting gas-liquid mixtures, where accurate velocity and flow rate measurements are critical for process optimization. Methods also enable real-time monitoring of multiphase flows without the need for bulky equipment, reducing the need for test separators and minimising production losses [51] [52].

Despite their advantages, cross-correlation methods face several limitations. Munir and Khalil (2015) identified signal attenuation and noise as major challenges, particularly in high-pressure or high-turbulence conditions. Besides, Muhamedsalih and Lucas [52] noted that electrode-based systems are sensitive to flow regime changes, requiring frequent recalibration. Monnet *et al.* [53] highlighted the complexity of integrating cross-correlation with other metering techniques, which increases system cost and maintenance requirements. Moreover, the accuracy of cross-correlation methods decreases in mist or churn flow regimes, where flow disturbances are less distinct [53]. To address these challenges, researchers have proposed several improvements, such as the use of advanced signal processing algorithms, such as machine learning, to enhance noise filtering and correlation accuracy [51]. Further suggestions are to optimise electrode configurations and incorporate adaptive calibration techniques to account for flow regime changes [52]. Another suggestion emphasized the need for hybrid systems that combine cross-correlation with other metering technologies, such as ultrasonic or gamma-ray sensors, to improve accuracy in complex flow conditions [53]. Future research could focus on developing compact, cost-effective cross-correlation systems for field applications, leveraging advancements in sensor technology and data analytics.

4.6. Microwave Sensors

Microwave sensing techniques have been extensively explored for multiphase flow metering, focusing on the measurement of oil, gas, and water phases. Manoj *et al.* [54] utilized microstrip patch sensors and near-field coaxial probes, employing reflection and transmission measurements to determine gas velocity and liquid flow rates. Similarly, Tayyab *et al.* [55] developed a low-cost, 28-port RF sensor designed to estimate dielectric constants through transmission coefficients. Sabzevari *et al.* [56] introduced a microwave sensing and imaging (MSI) system using ultrawideband synthetic aperture radar (UWB SAR) to create high-resolution 2D images of multiphase flows. Oon *et al.* [14] focused on cylindrical cavity sensors for detecting gas-liquid flow regimes, while van Maanen [57] investigated microwave resonance systems for detecting liquid water flow in wet gas meters. These microwave techniques were aimed at delivering high-resolution, real-time data for flow regime analysis, void fraction measurement, and water content estimation.

The principal equation for liquid fraction ϕ_l, is expressed using the Bruggeman model in Equation (6), where; $\varepsilon_l, \varepsilon_g$ are the permittivity of the liquid and gas phases, respectively, and ε_m is the effective permittivity of the wet gas flow mixture, and A_0 is the droplet shape factor.

$$\phi_l = 1 - \frac{\varepsilon_p - \varepsilon_m}{\varepsilon_p + \varepsilon_d}\left(\frac{\varepsilon_d}{\varepsilon_m}\right)^{A_0} \tag{6}$$

However, in terms of performance, the review established that these methods demonstrate promising results under varying operating conditions. Manoj *et al.* [54] achieved errors of less than ±10% for gas volume fractions (GVF) and water-liquid ratios (WLR), while Tayyab *et al.* [55] reported a similar ±10% error for dielectric constant estimation in oil-water-gas combinations [55]. The research by

Sabzevari *et al.* [56] achieved a maximum error of 3.8% for crude oil flow rates, highlighting the accuracy of the MSI system. While Oon *et al.* [14] validated the accuracy of cylindrical cavity sensors across multiple gas-liquid flow regimes, van Maanen [57] demonstrated the sensitivity of microwave resonance systems in high-pressure conditions but noted challenges in quantifying water content against dominant gas and condensate contributions [14].

Notwithstanding the potential of microwave techniques in wet gas flow, these methods face limitations and challenges, including sensitivity to noise and environmental factors like salinity and turbulence. Manoj *et al.* [54] identified calibration challenges and signal interference, while Tayyab *et al.* [55] suggested limitations in measuring materials with low permittivity contrast [55]. Sabzevari *et al.* [56] and Oon *et al.* [14] emphasized the need for careful calibration and reported difficulties in detecting low-contrast flow regimes. van Maanen [57] noted that gas and condensate contributions often mask the liquid water signal, reducing accuracy [57]. These challenges underscore the importance of robust signal processing and calibration techniques.

To address these challenges, researchers have proposed several improvements. Integration of machine learning algorithms for adaptive calibration and real-time analysis can enhance accuracy and reduce signal noise [54]. Advanced imaging techniques, such as time-domain global back-projection [56], and robust hardware designs can mitigate sensitivity to noise and low permittivity contrast. Moreover, hybrid metering systems that combine microwave sensors with other techniques, such as differential pressure [38], offer the potential for improved measurement accuracy in challenging multiphase environments. These advancements highlight the potential for continuous innovation in microwave-based multiphase metering technologies [38]. **Table 6** below summarizes the gap analysis based on the existing studies for microwave sensing technology in wet gas flow measurement.

4.7. Phase Fraction Sensing Technologies and Tomography

Phase fraction sensing technologies, such as gamma-ray detection, electric capacitance tomography (ECT), conductive impedance, and optical methods, are crucial for determining the composition of multiphase flows. Gamma-ray sensors, as investigated by Vestøl *et al.* [58] and Pan *et al.* [59], use radiation attenuation to estimate phase fractions, with designs ranging from dual-detector systems to densitometers. Electric capacitance tomography (ECT), investigated by Li *et al.* [60] and Da Silva *et al.* [61], maps phase fractions by leveraging the permittivity distribution. Conductive impedance systems, such as those by Wiedemann *et al.* [62], utilize electrode arrays to measure electrical properties in gas-liquid flows. Optical methods, as studied by Meng *et al.* [63], particularly focusing on production logging in challenging shale gas wells using coiled tubing fiber optic Flow Scanning Imaging (FSI). The method integrated optical fibres for real-time measurement of fluid velocity profiles, gas and water holdup, and detection of complex flow patterns.

Table 6. Gap analysis of microwave sensing technology for wet gas measurement.

Aimed Knowledge	Gap Identification	Desired Outcome	Reference
High accuracy in phase distribution measurements	Sensitivity to noise and environmental factors like salinity and turbulence affects measurement precision	Development of robust signal processing techniques and noise-resistant calibration methods	[54] [55]
Effective measurement in low-contrast flow regimes	Challenges in detecting materials with low permittivity contrast and low-contrast flow regimes	Advanced imaging techniques, such as time-domain global back-projection, for better detection in low-contrast scenarios	[55] [56]
Reliable performance under high-pressure conditions	Gas and condensate contributions mask liquid water signals, reducing accuracy	Improved hardware designs and integration with complementary sensors for enhanced signal discrimination	[14] [57]
Improved calibration for real-world applications	Calibration challenges in complex multiphase environments	Adaptive machine learning algorithms for real-time calibration and accurate flow regime detection	[14] [54]
Versatility across multiphase flow conditions	Limitations in accuracy for diverse flow regimes, including mixed gas-liquid flows	Hybrid systems combining microwave sensing with differential pressure meters or other techniques for comprehensive measurements	[38] [56]
Real-time high-resolution imaging of flow regimes	Existing systems lack sufficient resolution for detailed flow regime analysis	Implementation of microwave sensing and imaging systems with ultrawideband synthetic aperture radar (UWB SAR) for precise visualization	[56]
Accurate estimation of dielectric constants	Limited precision in dielectric constant measurements in oil-water-gas combinations	Development of multi-port RF sensor designs for improved permittivity contrast and precision	[55]

The performance of these technologies varies depending on flow conditions and calibration. Gamma-ray sensors demonstrated RMS errors below 6%, with Sharifzadeh *et al.* [64] emphasizing their reliability in controlled environments. ECT systems achieved uncertainties of ±5% - 10%, with improvements in electrode sensitivity noted by Iliyasu *et al.* [65]. Conductive impedance methods reported uncertainties of ±5% - 8% in multiphase flow measurements [65], while the optical techniques show high precision about ±2% - 5% and reliability, offering improved insights into gas production profiles and enabling effective evaluation of fracturing impacts [63]. The application of these phase fraction technologies spans industries such as oil and gas, chemical processing, and power generation. Gamma-ray sensors are widely used in nuclear power plants and pipelines for real-time phase fraction and flow rate monitoring. ECT is applied in chemical reactors and reservoir management, while impedance systems are valuable for monitoring pipeline flow conditions. Optical sensors, known for their non-intrusive nature, are particularly effective for water fraction measurements and production optimization in oil and gas wells [66].

However, each phase fraction method faces unique challenges that hinder its performance in wet gas metering. Gamma-ray systems are costly and present radiation safety concerns, limiting their broad adoption [59]. ECT systems require extensive calibration and exhibit resolution limitations in complex flow conditions [60]. Conductive impedance systems are sensitive to temperature fluctuations and polarization effects [62], while optical sensors are prone to contamination and require clean optical paths for accurate measurement. Generally, in phase fraction metering, the dependence on flow regime-specific calibration adds another layer of complexity for all these techniques.

To overcome these challenges, researchers have proposed a range of improvements. Gamma-ray systems could benefit from the development of non-radioactive alternatives and enhanced detector sensitivity [64]. Advancements in ECT may focus on improving resolution and combining the technology with hybrid sensing systems [60]. Conductive impedance methods could be enhanced through adaptive calibration techniques to mitigate temperature and polarization challenges [62]. Optical methods can benefit from self-cleaning systems to ensure robust performance in contaminated settings, optimise signal processing algorithms, and enhance tool robustness to handle varying well conditions effectively [63]. Exploring hybrid approaches that integrate these phase fraction sensing technologies with differential pressure or ultrasonic meters could further enhance their adaptability and accuracy in diverse operational scenarios. **Table 7** below summarizes the gap analysis based on the existing studies in phase fraction metering methods in wet gas flow measurement.

Table 7. Gap analysis of phase fraction sensors other than microwave for wet gas measurement.

Aimed Knowledge	Gap Identification	Desired Outcome	Reference
Accurate phase fraction estimation	Gamma-ray systems face high costs and radiation safety concerns, limiting their widespread application	Development of cost-effective, non-radioactive alternatives with improved detector sensitivity	[58] [59] [64]
High-resolution imaging in complex flow conditions	ECT systems require extensive calibration and have resolution limitations under complex flow regimes	Enhancement of ECT resolution and integration with hybrid sensing systems	[60] [61]
Reliable measurements across temperature ranges	Conductive impedance methods are sensitive to temperature fluctuations and polarization effects	Development of adaptive calibration techniques to mitigate temperature sensitivity	[62] [65]
Non-intrusive and contamination-resistant sensors	Optical sensors are prone to contamination and require clean optical paths for accurate performance	Self-cleaning systems and optimization of optical signal processing algorithms	[37] [61]
Reduced reliance on flow regime-specific calibrations	All techniques heavily depend on flow regime-specific calibrations, limiting adaptability in dynamic flows	Introduction of real-time adaptive algorithms and hybrid approaches	[37] [60]
Enhanced adaptability in diverse applications	Each method struggles with specific operational challenges, reducing its broad applicability	Hybrid metering systems combining gamma-ray, ECT, impedance, and optical technologies for improved versatility	[37] [38] [59]

5. Trends in Wet Gas Measurement

The review in this paper presents the efforts in measurement technology to improve wet gas metering in applicable industries, such as oil & gas, petrochemical, steam, and environmental monitoring. Based on the drawbacks of existing methods, the innovation trends are directed at areas of knowledge like applying robust signal processing techniques, developing sophisticated sensors, and real-world experiments, as discussed in this chapter.

5.1. Machine Learning in Wet Gas Measurement

The critical review suggests that data-driven Machine learning (ML) techniques have emerged as a transformative tool in wet gas measurement, offering advanced data-driven solutions to address the complexities of multiphase flow. Hosseini *et al.* [67], [68] explored the application of ML algorithms to predict gas and liquid flow rates directly, bypassing traditional correlation-based methods. Their study demonstrated that models like Random Forest Regression (RFR) and Multilinear Regression (MLR) achieved uncertainties as low as 0.35%, significantly improving measurement accuracy. Similarly, [48] developed ML-based over-reading correction models for ultrasonic flow meters, incorporating variables such as Liquid Volume Fraction (LVF) and Lockhart-Martinelli parameters. These models reduced uncertainties to 0.49%, enhancing the reliability of ultrasonic meters in wet gas conditions. Research by Wang *et al.*, (2020) investigates the application of the machine learning (ML) method using Deep Neural Network (DNN), Support Vector Machine (SVM), and Convolutional Neural Network (CNN) for estimating multiphase flow rates using time-series sensing data. Using Venturi tube data, the method demonstrated superior performance in predicting liquid and gas flow rates [69]. However, Wang *et al.* [69] suggested that future research should focus on refining data pre-processing techniques, incorporating hybrid ML models, and optimizing real-time calibration methods. Besides, Grayzlov *et al.* (2021) achieved an error of around 1.25% for multiphase flow prediction rate with Artificial Neural Network (ANN), Gated Recurrent Unit (GRU) prediction model, and 5% with Extreme Gradient Boosting ANN machine learning model [70]. These ML models leverage adaptive algorithms that dynamically adjust their parameters based on incoming sensor data, ensuring robust performance even in fluctuating environments. Online prediction systems allow models to refine their estimations by incorporating new data streams, reducing errors caused by sudden shifts in gas-liquid ratios. Moreover, continuous adaptation frameworks employ retraining cycles to mitigate data drift, ensuring that predictions remain accurate despite evolving conditions.

Machine learning models like Random Forest Regression (RFR) and Multiple Linear Regression (MLR) are widely used in wet gas metering applications, but they face several limitations in dynamic flow conditions. RFR, despite its robustness, can be sensitive to noisy sensor data, leading to inconsistencies in predictions [71]. Its computational complexity makes real-time deployment challenging, especially when dealing with large datasets [72]. Additionally, RFR performs best within trained data ranges but struggles with extreme, unseen conditions. The model's accuracy is also dependent on well-engineered features, requiring careful selection and pre-processing to maintain reliability [68]. On the other hand, MLR assumes a linear relationship between variables, which often does not hold in complex wet gas flows [67]. It struggles with nonlinear interactions, making it less effective for capturing intricate dependencies between gas-liquid parameters [73]. Multicollinearity among features can distort MLR predictions, reducing their reliability [74]. Furthermore, the model lacks adaptability in adjusting to varying flow regimes, limiting its effectiveness in real-time applications [72].

5.2. Hybrid Metering Technologies

Hybrid metering systems, which combine multiple measurement techniques, are gaining traction for their ability to address the limitations of individual methods. Hybrid techniques involve the integration of a single-phase flow meter and a phase fraction sensor. The Dualstream FALCON by Solartron ISA exemplifies this trend, integrating differential pressure (DP) meters with advanced digital instrumentation to provide real-time three-phase flow rates [75]. This system is particularly effective in high-temperature and sour gas environments, achieving high accuracy and operational safety. Lao *et al.* [13] reviewed hybrid systems that combine DP meters with phase fraction sensors, such as gamma-ray or microwave sensors, to improve accuracy in challenging conditions [13]. These systems demonstrated enhanced performance, with uncertainties reduced to ±2% - 3% for gas flow rates [29]. Hybrid technologies are increasingly applied in offshore and unconventional gas fields, where complex flow dynamics demand robust solutions. Hybrid metering systems address the limitations of single-phase flow meters in wet gas measurement by integrating multiple measurement principles to enhance accuracy and adaptability.

Hybrid metering systems address the limitations of single-phase flow meters in wet gas measurement by integrating multiple measurement principles to enhance accuracy and adaptability. Traditional single-phase meters, such as Differential Pressure (DP) meters and Venturi meters, often struggle with liquid presence, leading to overestimated gas flow rates [76]. Hybrid systems, however, combine vortex flow meters, Coriolis meters, and phase fraction sensors, allowing for improved liquid fraction detection and compensation for environmental variations like pressure and temperature changes [77]. Performance metrics that show improvements include measurement accuracy, where hybrid meters reduce errors caused by phase slip and varying gas-liquid ratios [68]. Repeatability is enhanced by integrating multiple sensors, ensuring consistent readings across different flow regimes [67]. Robustness improves as hybrid systems adapt to dynamic conditions, reducing recalibration needs [73]. Additionally, uncertainty quantification is more reliable, as hybrid meters leverage machine learning models to refine predictions [74].

Integrating machine learning (ML) and hybrid metering systems in small-scale or emerging industries presents both opportunities and cost challenges. Although these technologies improve accuracy and efficiency in wet gas measurement, their deployment requires an initial investment in sensor integration, computational resources, and model training [78]. Cloud-based ML solutions can lower upfront costs by providing scalable computing resources without the need for substantial hardware investments. However, ongoing expenses, such as data storage, model maintenance, and system calibration, can increase operational costs [78]. To manage expenditures, businesses can implement cost-cutting strategies like optimising computational resources and streamlining data processing. Moreover, utilising open-source ML frameworks and pre-trained models can minimise development costs while preserving predictive accuracy [78].

5.3. Phase Fraction Sensing Technologies

Phase fraction sensing technologies, such as gamma-ray and electric capacitance tomography (ECT), continue to play a critical role in wet gas measurement. Gamma-ray sensors, as reviewed by Pan *et al.* [59], achieved RMS errors below 6%, making them reliable for real-time monitoring in pipelines [59]. ECT systems, optimized by Iliyasu *et al.* [65], delivered uncertainties of ±5% - 10%, with applications in chemical reactors and reservoir management. However, the application of microwaves has captivated the interest of many researchers since it has gained massive application in wet gas measurement for efficient liquid detection and phase [38]. These technologies are increasingly integrated into hybrid systems to enhance their adaptability and accuracy. **Figure 6** below illustrates the trend of wet gas metering technologies based on complexity and cost of investment and operation. This innovation trend, based on accuracy, complexity, and cost, has been derived from the current review of this paper.

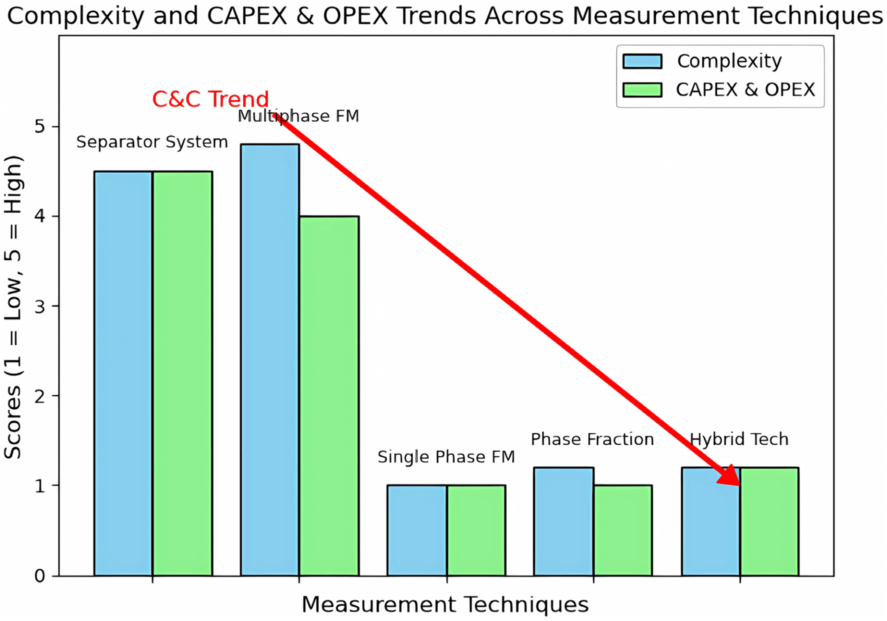

Figure 6. Wet gas metering technology trend.

6. Performance Evaluation and Comparative Analysis

The performance of various wet gas metering techniques is evaluated based on reviewed data in this study and presented in Figure 7 and Table 8 below. As summarized in Table 8 below, the non-intrusive ultrasonic and Coriolis flow meters offer superior measurement accuracy as stand-alone flow meters. The improvement seems to become realistic when the flow meter is integrated with a phase fraction sensor to create the hybrid metering system, which further enhances the accuracy to 1% as presented in Table 8 below. Although the uncertainty presented in Figure 7 shows great improvement with the Hybrid and ultrasonic flowmeter, the literature stresses the integration of the machine learning optimization model (ML) to further enhance the accuracy and reliability of the metering techniques, as proved in [67] [69] and [65]. It was further observed by Iliyasu *et al.* [65] that

Table 8. Performance analysis of various wet gas metering technologies.

Method	**Reference Author**	**Performance**	**Merits of Wet Gas**	**Limitations**	**Trend**
Differential Pressure (DP) Meters: Venturi, Orifice Plate, V-Cone	[13] [31]	±2% - 5% for gas flow rate	• Reliable and cost-effective • Handles high-pressure conditions well • Broad industry adoption and familiarity • Wide operating range across flow conditions	• Overestimates gas flow in wet conditions • Requires correction factors for liquid presence • Sensitive to flow regime changes	Increasing use in hybrid systems combining DP meters with other sensors for improved accuracy
Ultrasonic Flow Meters	[1] [11] [79]	±1% - 3% for gas flow rate	• Non-intrusive • High accuracy for multiphase flows • Minimal pressure drop • Suitable for monitoring challenging flow regimes	• Expensive • Requires clean gas for optimal performance • Limited durability in harsh conditions	Increasing integration with IoT for real-time monitoring
Coriolis Flow Meters	[46] [47]	±2% - 4% for mass flow rate	• Measures mass flow directly • High rangeability • Suitable for custody transfer • Handles a wide range of fluids	• Affected by multiphase conditions • Requires advanced corrections for wet gas • High susceptibility to vibration interference	Advancements in sensor design for better multiphase performance
Microwave Sensors	[31] [55] [56]	±5% for liquid fraction	• Non-invasive • Effective for detecting liquid fractions • Capable of high-frequency data collection • Reliable in high-salinity environments	• Limited to specific applications • Affected by high gas-liquid ratios • Susceptible to signal attenuation in certain conditions	Emerging as a complementary technology for phase fraction measurement
Gamma-Ray Sensors	[31]	±3% - 5% for phase fraction	• Effective for phase fraction measurement • Works in extreme conditions • High penetration capability • Insensitive to flow regime variations	• Radiation safety concerns • Expensive • Heavy shielding is required for safe operation	Limited use due to safety and cost concerns

Continued

Electrical Capacitance Tomography (ECT)	[60] [61]	±5% - 10% for phase fraction	• Visualizes flow patterns • Non-invasive • Real-time phase distribution mapping • Compact and portable	• Limited resolution • Requires calibration for specific conditions • Affected by material permittivity variations	Emerging as a diagnostic tool for multiphase flows
Hybrid Systems	[31]	±1% - 2% for gas and liquid flow rates	• Combines the strengths of multiple methods • High accuracy in challenging conditions • Addresses flow regime changes • Flexible for various industrial applications	• Complex and expensive • Requires advanced calibration • Longer maintenance and repair times	Increasing adoption in subsea and offshore applications
Dual Methods (e.g., Venturi + Gamma-Ray)	[31] [80]	±2% - 3% for gas flow rate	• Enhances accuracy by combining complementary techniques • Suitable for extreme conditions • Reduces dependency on single-phase assumptions • Minimizes over-reading in wet gas	• Expensive • Requires integration of multiple systems • Calibration complexity due to the combination of diverse technologies	Growing use in high-accuracy applications like oil and gas pipelines

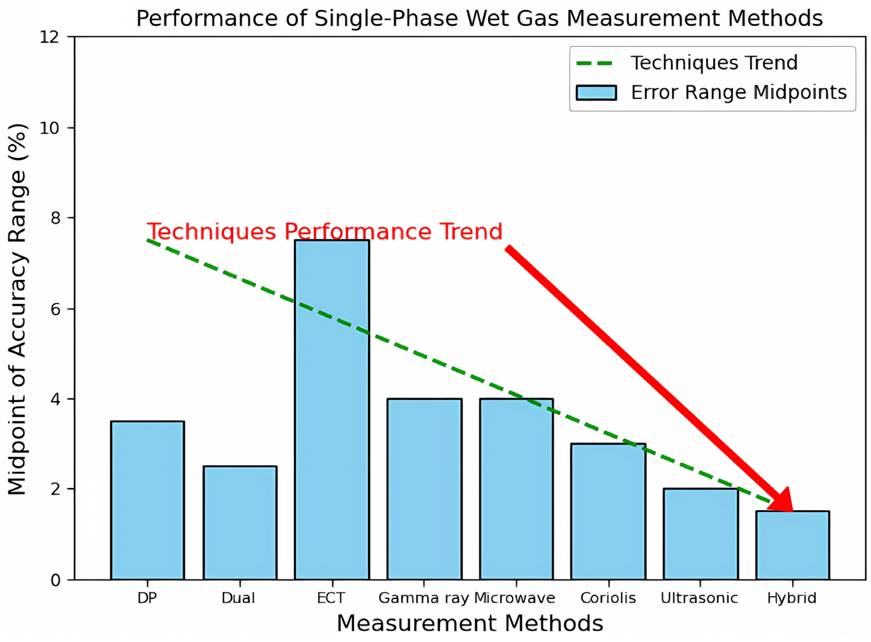

Figure 7. Performance of wet gas metering technologies based on their measurement uncertainty.

expanding the use of machine learning (ML) algorithms is vital for enhancing real-time calibration and adapting to varying flow regimes, thereby improving measurement accuracy in complex multiphase flows [65].

7. Real-World Applications of Wet Gas Metering

In real-world applications, wet gas metering plays a crucial role in pipelines, subsea systems, and process industries, addressing unique operational challenges while optimizing efficiency and resource allocation. For instance, TOTAL has implemented wet gas metering systems in the Gulf of Mexico to measure gas flow rates and liquid contents in line directly. This approach eliminates the need for test separators and enhances production efficiency in high-pressure systems. In subsea applications, the Roxar Subsea Wetgas Meter by Emerson addresses extreme conditions by providing real-time measurements of water, gas, and condensate flow rates. It also detects salinity to prevent hydrate plugs. These systems operate effectively at ultra-high gas volume fractions (GVF of 99% - 100%), thereby improving production and flow assurance in deepwater natural gas fields [81]. In the process industries, wet gas metering supports reservoir management, production optimization, and compliance with environmental regulations. Ultrasonic flow meters, commonly used in wet gas fields, offer high rangeability and minimal pressure drop [45] [57], ensuring accurate allocation in fiscal systems. Furthermore, advancements in machine learning have significantly enhanced the accuracy and real-time analytical capabilities of wet gas meters in process environments [67]. Through these various applications, wet gas metering technologies demonstrate their indispensable role in modern industrial operations. **Table 9** below presents selected and commonly used metering systems that exist in the oil and gas industry for wet gas flow measurement.

Table 9. Examples of common metering systems currently available on the market for wet gas measurement.

Device	Properties	Performance	Applications	Limitations
Roxar Subsea Wetgas Meter [82]	Microwave resonance technology, integrated salinity measurement	High sensitivity to water content, continuous real-time monitoring	Wet gas well streams, subsea applications	Sensitivity to liquid loading requires regular calibration
Roxar 2600 Multiphase Flow Meter [83]	Online measurements of oil, water, and gas rates	Accurate measurements from 0 - 100% gas volume fraction and 0 - 100% water liquid ratio	Well testing, production metering, and wellhead monitoring	Accuracy is affected by high liquid content and complex installation
Krohne OPTIMASS 6400 [84]	Coriolis mass flow meter with integrated microwave technology	High precision and reliability in multiphase flows	Wet gas applications, challenging conditions	Performance varies with liquid fraction and needs sophisticated data processing
Siemens SITRANS FM MAG 8000 [85]	Electromagnetic flow meter with microwave technology	Robust performance, minimal maintenance, suitable for remote locations	Wet gas measurement, remote locations	Sensitivity to electromagnetic interference requires regular maintenance
Daniel Ultrasonic Meter [2]	Inline, high turn-down ratio, no pressure drop	Operational uncertainties 2% - 5%, over-reading correction needed	Sales allocation, well reservoir management	Accuracy is affected by high liquid content and complex installation
Krohne Ultrasonic Meter [86]	Inline, large rangeability, minimal pressure drop	Requires a correction algorithm for liquid fractions	Wet gas applications, field performance	Performance varies with liquid fraction and needs sophisticated data processing

8. Unsolved Issues in Wet Gas Measurement: Challenges and Gaps in Knowledge

Wet gas measurement remains an integral part of multiphase flow metering in industries like oil and gas, yet several challenges continue to hinder precise and reliable measurement under varying operational conditions. One of the most critical issues is the reliance on calibration for specific flow regimes, which reduces the adaptability of systems such as differential pressure (DP) meters, ultrasonic flow meters, and phase fraction sensors. These technologies depend on empirical models, which are unable to accommodate dynamic gas-liquid compositions. Real-time adaptable calibration techniques using machine learning (ML) algorithms, as highlighted by Xu *et al.* (2017) and Lao *et al.* (2023), are essential for enhancing the reliability of wet gas meters in diverse conditions. Noise interference and signal attenuation also present significant challenges, with technologies like ultrasonic flow meters and gamma-ray sensors suffering from errors in turbulent environments or at high gas volume fractions [48] [59].

Phase fraction sensing technologies, including gamma-ray sensors, electric capacitance tomography (ECT), and optical methods, face hurdles in achieving high resolution, sensitivity, and accuracy. Radiation safety concerns limit the widespread use of gamma-ray systems, while ECT struggles with low resolution in dynamic flow patterns [59] [65]. Optical methods, despite being non-invasive, are prone to contamination, which impairs measurement accuracy [62]. Furthermore, meters operating under high gas volume fraction (GVF) or low liquid volume fraction (LVF) conditions encounter unique obstacles, such as masking effects from dominant gas phases, leading to under-reading or over-reading errors [31]. Hybrid systems that integrate complementary technologies could be a promising avenue for addressing these limitations.

Other barriers include environmental sensitivity, such as salinity and temperature variations, which negatively impact the accuracy of sensors like microwave and impedance-based systems [62]. Moreover, the lack of standardized testing and validation protocols across industries limits the scalability and global adoption of these technologies. Most systems are tested under controlled laboratory conditions, which fail to replicate the complexities of real-world applications [38]. Establishing universal testing standards, along with advancements in computational tools like CFD models and digital twins, will be crucial for improving the performance and reliability of wet gas measurement systems. **Table 10** below summarizes the generally unsolved challenges in metering technology related to wet gas measurement.

9. Recommendations and Future Direction

The increasing demand for accurate and efficient wet gas measurement in industries like oil and gas underscores the need for continual advancements in technologies and methodologies to address the challenges of multiphase flow metering. This review recommends potential future directions for addressing current limitations while building on existing innovations.

Table 10. Unsolved challenges with existing wet gas metering technologies.

Challenges/Unsolved Issues	Improvements Required	Reference	Future Directions
Dependence on Calibration	• Develop adaptive calibration techniques for real-time adjustments • Incorporate machine learning for dynamic calibration across varying flow conditions	[30] [31]	• Utilize real-time learning algorithms • Create calibration-free systems capable of self-adapting to changes in flow parameters
Noise Interference and Signal Attenuation	• Design robust transducers with enhanced noise filtering • Implement advanced signal processing algorithms	[48] [59]	• Test noise-resistant systems under turbulent flow conditions • Combine multiple noise-mitigation strategies in hybrid systems
Limitations in Phase Fraction Sensing	• Develop hybrid systems combining complementary sensing techniques • Improve resolution and sensitivity of phase fraction sensors (e.g., ECT, gammaray)	[59] [65]	• Integrate phase fraction technologies with hybrid metering • Explore non-invasive and safer alternatives for gamma-ray sensors
Challenges in High GVF and LVF Conditions	• Enhance algorithms to compensate for dominant gas or liquid contributions • Validate hybrid systems in extreme GVF/LVF environments	[30] [31]	• Develop systems tailored for high-GVF wells. Leverage computational models for extreme flow condition simulation and analysis
Sensitivity to Environmental Conditions	• Adapt sensors to withstand extreme salinity, temperature, and pressure variations • Use materials designed for harsh environmental conditions	[62]	• Create environmental simulations for sensor validation • Incorporate digital twin models to predict performance under extreme conditions
Lack of Standardized Testing and Validation	• Establish universal testing protocols for field environments • Collaborate with industry for validation across multiple sites and scenarios	[38]	• Expand field-testing initiatives • Foster industry-academic partnerships

Adopt Machine learning (ML) optimization models in wet gas metering systems. ML has shown immense potential in achieving real-time calibration and improving accuracy. For instance, techniques such as Random Forest and Multilinear Regression demonstrate uncertainties as low as ±0.35%, and further development of adaptive ML algorithms could reduce calibration dependency while enabling systems to learn from dynamic flow conditions [68]. Also, expanding training datasets derived from field applications would enhance the reliability of these ML-driven solutions. Another future direction is the expansion of integration of hybrid metering systems, combining technologies like differential pressure meters, gamma-ray sensors, ultrasonic flowmeters, and optical systems, which offer another avenue for addressing the limitations of stand-alone techniques. Examples like the Dualstream FALCON meter show reduced uncertainties of ±2% - 3% for gas flow rates [75], and future designs should focus on compact, cost-effective systems to meet challenges in both onshore and offshore applications.

Improved sensor and hardware design remains a crucial area for innovation. High-sensitivity sensors, such as microwave resonators, electric capacitance tomography arrays, and self-cleaning optical systems, can mitigate signal noise and environmental interference. In parallel, the exploration of next-generation materials capable of withstanding extreme pressures, temperatures, and chemical exposure is critical to enhancing durability and performance in hostile environments, including sour gas and unconventional fields. Extensive field testing under diverse conditions is essential to validate the reliability and scalability of these advancements, complemented by the establishment of standardized testing protocols to foster comparability and widespread adoption [87].

Incorporating advanced computational techniques like digital twins can transform wet gas measurement by enabling real-time simulation, predictive maintenance, and operational optimization. Pairing these models with real-time sensor data enhances measurement accuracy and insight into system performance. Lastly, sustainability and cost efficiency must be emphasized, with a focus on energy-efficient designs to minimize environmental impact. Simplified plug-and-play systems can reduce operational expenses, while modular, scalable designs enhance adaptability for remote locations and marginal fields. These recommendations collectively highlight pathways to overcoming current limitations, promoting innovation, and ensuring that wet gas metering technologies evolve to meet the dynamic demands of modern industrial applications.

10. Conclusion

The discussion has comprehensively addressed the outlined specific objectives. It highlighted trends and advancements in wet gas metering techniques, focusing on innovative systems such as dual differential pressure (DP) meters, hybrid configurations, and machine learning integration for real-time calibration. These advancements demonstrate a shift toward adaptive and multi-technology approaches to improve accuracy and reliability. The performance evaluation of metering technologies identified key metrics, including uncertainties of ±2% - 3% for gas flow rates in hybrid systems and errors below ±0.35% using ML algorithms, showcasing their efficiency under diverse flow regimes. Challenges and limitations were critically analyzed, emphasizing issues like calibration dependency, noise interference, environmental sensitivity, and operational constraints in high gas volume fraction (GVF) and low liquid volume fraction (LVF) scenarios. Recommendations were proposed, including the use of machine learning for adaptive calibration, hybrid systems for comprehensive solutions, and advanced computational methods like digital twins for predictive capabilities. Industry applications were thoroughly explored, showcasing systems like TOTAL's pipeline wet gas metering and Emerson's Roxar Subsea Wetgas Meter, and assessing their suitability for specific requirements such as high-pressure pipelines and deepwater operations. This review not only provides actionable insights but also establishes pathways for future research and innovation in wet gas measurement technologies.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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