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Flow Measurement of Wet CO_2 Using an Averaging Pitot Tube and Coriolis Mass Flowmeters

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ABSTRACT

The flow measurement of wet-gas is an active field with extensive research background that remains a modern-day challenge. The implication of wet-gas flow conditions is no different in Carbon Capture and Storage (CCS) pipelines. The associated complex flow regime with wet-gas flow makes it difficult to accurately meter the flow rate of the gas phase. Some conventional single-phase flowmeters like the Coriolis, Orifice plate, Ultrasonic, V-Cone, Venturi and Vortex have been tested for this application, usually accompanied with special recommendations. Often, a correlation equation valid within a certain range of specific conditions is required to correct the response of the flowmeter. This paper presents investigations into the suitability and performance of one of the most advanced averaging pitot tubes for the flow measurement of wet CO_2 gas. The averaging pitot tube with flow conditioning wing geometry (APT-FCW) was studied and experimentally assessed in earlier work for the flow measurement of pure and dry CO_2 within an error of ±1%. Under wet-gas conditions, however, the APT-FCW sensor is found to give an error of up to ±25% and within ±1.5% after appropriate correcting solutions are applied for a liquid fraction of up to 20%.

Keywords – Carbon capture and storage; CO_2 gas; CO_2 transportation; Wet-gas flow; Averaging Pitot tube; Flow conditioning wing; Coriolis mass flowmeters.

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1. INTRODUCTION

The development and deployment of Carbon Capture and Storage (CCS) technologies have been accepted worldwide to reduce CO_2 emissions from fossil fuel fired industrial processes such as coal and gas-fired power stations, gas processing and bio-ethanol production [1]. Wet-gas such as saturated steam generally consists of inhomogeneous fluids of predominately gas component and a small amount of liquid in the mixture. This subset of two-phase flow is commonly encountered in a wide variety of industries, particularly in oil and gas and chemical production sectors. The CO_2 flow in CCS pipelines is no exception to this flow condition. The formation of wet-gas conditions in CCS transportation pipelines may result from events such as when the CO_2 gas passes through a choke valve at high pressure. The presence of liquid-form fluids like gas condensation in the CO_2 gas stream poses serious problems for accurate flow measurement which can significantly affect the measurement uncertainty of the flowmeter or even damages flowmeter in some cases [2]. Since the accurate accounting and measurement of CO_2 plays an important role through fiscal metering of the gas in CCS pipelines, a good knowledge of the effect of the liquid content on the flowmetering instrument is therefore required in quantifying and compensating the uncertainties in the flow measurement as well as ensuring an efficient and sustainable economic outcome. Resultantly, proper and accurate accounting is necessary as around 0.5% liquid by volume in the gas stream can cause up to 10% error in the readings of the gas meter. Excess incurred cost in production is another crucial concern in wet-gas metering where, for example, a 2% error for a large gas field could result in a financial exposure of about £1.75 million per year [3].

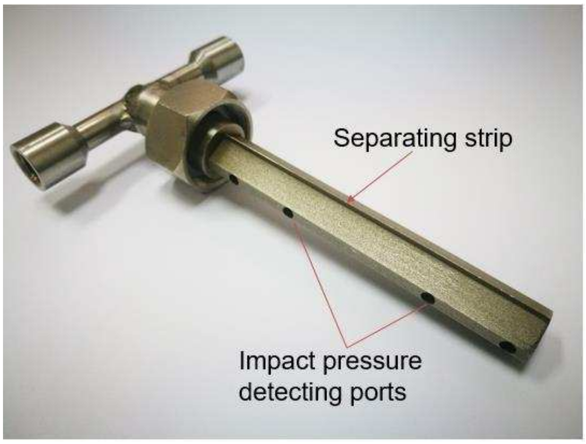
Extensive research over the past few decades have been carried out in wet-gas flow measurement but accurate metering of the mixture remains to be fully resolved. The use of differential pressure (DP) flowmeters such as those based on the Venturi and Orifice plate [4-6] and the Pitot tube [7, 8] for wet-gas flow metering have been investigated. More recent methods for gas-liquid two-phase flow measurement include the flow sampling technique [9], Ultrasonic meters [10] and batch sampling [11].

Depending on the flow measurement technique or combinations of, nature of the experimental setup, test matrix and level of liquid content, the wet-gas measurement error can be up to ±50% [4-11]. The wetness of the mixture can be determined using techniques such as mixture sampling, tracer method and pressure loss ratio between the DP instrument and two separate upstream and downstream pressure sensors. Other methods include advanced signal processing by observing the liquid content effect on the measured variables of the flowmeter such as shift in the speed-of-sound in ultrasonic meters, erroneous density measurement in Coriolis flowmeters and pressure fluctuations in DP meters. In this study, water is diluted with pure and dry CO_2 gas at various proportions under a pressure of less than 10 bar. Although the CO_2-water mixture forms a weak carbonic acid (H_2CO_3) which corrodes the pipe walls over time, it has been empirically proven that the corrosive property of the compound is only severe at high pressure conditions [12]. When no free water is present, the corrosion rate is as low as 0.2mm per year for low carbon steel material [12]. Coriolis mass flowmeters (CMF) have been widely known for their performance in various custody transfer applications and they are becoming an important option for multiphase flow applications [13]. In this paper, a combination of multiple CMFs is used to measure the mass flow of each fluid component of the wet CO_2. An averaging Pitot tube with flow conditioning wing (APT-FCW) is setup in a horizontal-testing configuration during this experimental procedure and referenced against the single-phase CO_2 gas CMF unit. The APT-FCW prototype is designed to produce high DP signals and, as a result, reduces measurement error at low flow rates as well as improving overall measurement uncertainty [14]. Previous experimental research has indicated that the APT-FCW is capable of metering pure gaseous CO_2 within an error of ±1% [15]. The effect of various fractions of liquid content in the gas stream on the performance of the flow sensor is investigated in this present research. Accurately discerning the actual flow distribution such as the void fraction or visual description of the different fluids within the pipeline is outside the scope of this paper. Instead, the metrological performance of the APT-FCW for this particular two-phase flow scenario is evaluated.

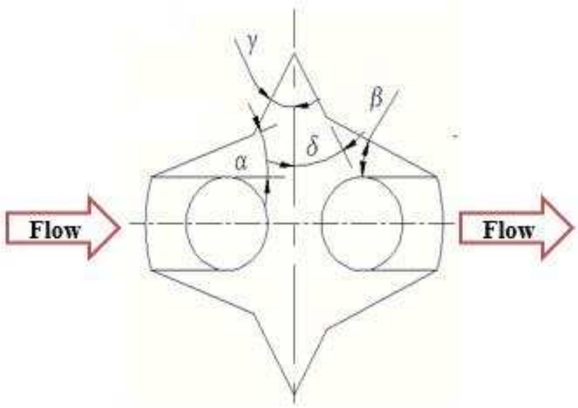
2. SENSING PRINCIPLE

(a) Average Velocity and Flow Rates

Averaging pitot tubes are generally known for their lack of moving parts, simple and compact installation, high accuracy, optimization for minimal pressure loss, wide temperature and pressure tolerance and application in large diameter pipes. The multiple laterally arranged sensing ports on its probe extends across the entire cross section of the pipe to provide average flow rate measurement. The impact pressure and blockage pressure generated at the front and rear of the sensor's probe, respectively, are transmitted through separate tubes to a differential pressure (DP) sensor. In addition to producing higher DP signal values compared to other conventional models, the flow conditioning wing (FCW) scheme also offers a high level of accuracy and repeatability [14]. Fig. 1 shows the APT-FCW and its corresponding cross sectional shape, while Fig. 2 represents its operating principle.



(a) APT-FCW.



(b) Cross sectional shape [14].

Fig. 1. Picture and cross section of the APT-FCW where α=30°, β=15°, δ=30° and γ=35°

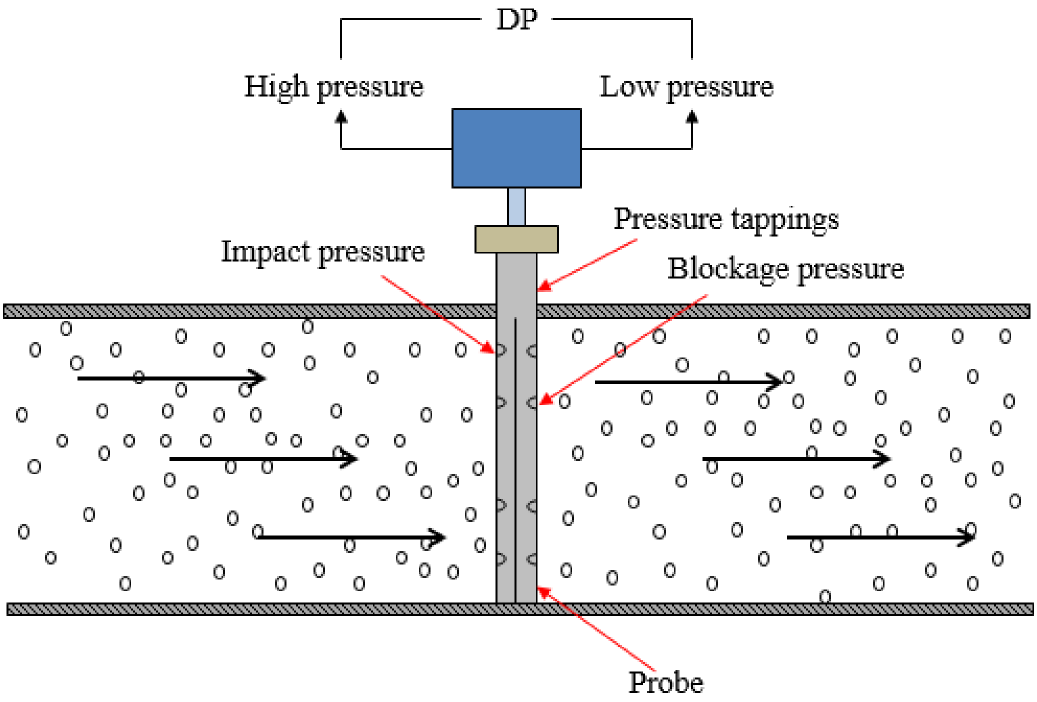


Fig. 2. Operating principle of the APT-FCW.

The measured pressure difference by the APT-FCW sensor at the point of installation in the flow stream is a direct function of the average flow velocity of the mixture which is calculated as: –

$$\bar{V} = K\sqrt{\frac{2\Delta P}{\rho}} \tag{1}$$

where $\bar{V}$ is the average flow velocity in m/s, K is the average meter factor of the sensor (= 0.50909), ΔP is the theoretical differential pressure across the sensor (the difference between the total pressure and the static pressure) in Pa and ρ is the density of the fluid in kg/m^3.

The meter factor of the flow sensor was initially predicted from computational fluid dynamics (CFD) simulations and experimentally finalized based on the conditions of a 1-inch pipe [14]. This correcting factor compensates for thermal expansion, discharge coefficient and gas expansion factors under these conditions. The density of the fluid is calculated as:–

$$\rho = \frac{P}{RT} \tag{2}$$

where P is the absolute flow pressure in Pa, R is the specific gas constant (CO_2 = 188.9 J/kg K) and T is the flow temperature in K.

Following these calculations, relevant flow rates and the total measured mass can be obtained using the following equations:

$$q_v = \bar{V}(\pi \frac{D^2}{4}) \tag{3}$$

$$q_m = \rho\bar{V}(\pi \frac{D^2}{4}) \tag{4}$$

$$Q_m = q_m t \tag{5}$$

where D is the internal diameter of the pipe in m, q_v is the volumetric flow rate in m^3/s, q_m is the mass flow rate in g/s, t is the flow run time in seconds and Q_m is the totalized mass in grams.

(b) Flow Rate Correction

Generally as with most DP-based flowmeters, the output signal of the APT-FCW through the DP transmitter is expected to "over-read" due to the presence of the liquid in the gas stream. The extent of this over-read depends mainly on the volume of the liquid content relative to the total volume of the wet-gas mixture at certain flow conditions. Other influential factors include type of meter, liquid phase properties, gas velocity, gas density and flowmeter diameter ratio [2]. It is therefore necessary to compensate or correct this over-read to obtain the actual reading of the flowmeter. A correction factor inherently based on the DP transmitter's true output under dry or single-phase gas conditions has been developed and applied to the device's indicated reading which is then used in subsequent computation of other flow equations [2]. Other varieties of available correlation equations like those proposed by Murdock, Chisholm and de Leeuw for correcting the over-read of other closely related DP flowmeters like the Orifice plate and Venturi tubes [5, 6] appear applicable to the APT-FCW under strict flow boundaries, but a more direct approach is taken in this research. Nevertheless, these correlation models are tested to evaluate their effectiveness on the APT-FCW sensor, which is discussed in later sections. The meter's over-read is calculated as:–

$$OR = \sqrt{\frac{\Delta P_{wg}}{\Delta P_g}} \tag{6}$$

The corrected or actual DP reading therefore becomes:

$$\Delta P_{corrected} = \frac{\Delta P_{wg}}{OR} \tag{7}$$

With this, the average flow velocity and mass flow rate of the dry gas and wet-gas can be written separately as:–

$$\bar{V}_g = K\sqrt{\frac{2\Delta P_g}{\rho}} \tag{8}$$

$$\bar{V}_{wg} = K\sqrt{\frac{2\Delta P_{wg}}{\rho}} \tag{9}$$

$$q_{m(g)} = \rho \bar{V}_g (\pi \frac{D^2}{4}) \tag{10}$$

$$q_{m(wg)} = \rho \bar{V}_{wg} (\pi \frac{D^2}{4}) \tag{11}$$

where the terms g and wg denotes dry gas and wet-gas, respectively.

In terms of measured mass flow, Equation (6) can be interpreted as;

$$OR_{mass} = \left[\frac{q_{m(indicated)}}{q_m} - 1\right] \times 100\%$$

(12)

(c) Wetness of Mixture

As there is currently no universally defined or accepted gas-liquid ratio for a wet-gas mixture, the Lockhart-Martinelli parameter ($X_{L\text{-}R}$) serves as the closest and best available standard for characterizing the wetness of the mixture [6]. In the context of these experiments and as with most of the industry, wet-gas is classified in this paper as $0.005 \leq X_{L\text{-}R} \leq 0.3$ or simply $X_{L\text{-}R} \leq 0.3$ where $X_{L\text{-}R} >$

0.3 is inferred as multiphase flow [4, 6]. The dimensionless L-R parameter can be conceived from a number of different parameters but in this paper, this is written as:–

$$X_{L-R} = \frac{q_l}{q_g}\sqrt{\frac{\rho_g}{\rho_l}} \tag{13}$$

where q_l and q_g are the mass flow rates of the liquid and gas components, respectively, in g/s and ρ_l and ρ_g are their respective densities in kg/m^3.

3. EXPERIMENTS

Experiments were conducted on a main flow pipe with 22.14 mm internal diameter and 1.65 mm wall thickness as shown in Fig. 3. CO_2 gas was supplied from a vessel-skid system at a discharge temperature of around 20^{o}C and water was delivered through a 4-bar rating domestic pump with pressure control using a pressure-reducing valve. The maximum operating pressure of the flow rig system was 10 bar. The test section was positioned 1.2m upstream and 1.8m downstream on the pipe. Two CMFs were connected on each fluid component line to measure and monitor their respective flow rates. The fluid component supply lines were both of 12 mm in inner diameter. One of the CMF, with a 600 kg/h range and gas metering accuracy of ±0.35%, was installed on the CO_2 gas line while the other CMF with a much lower range model of 36 kg/h and ±0.2% accuracy was fitted on the water flow line. A DP transmitter with an uncertainty of ±0.075% of the set span/range was located adjacent to the metering test section. The desired flow rate on the fluid feed lines was appropriately regulated using high-precision manually operated control valves while a mixer was used to combine the fluids into the main pipeline. Steady-state pressure control and stability were maintained through a backpressure regulating unit downstream of the APT-FCW.

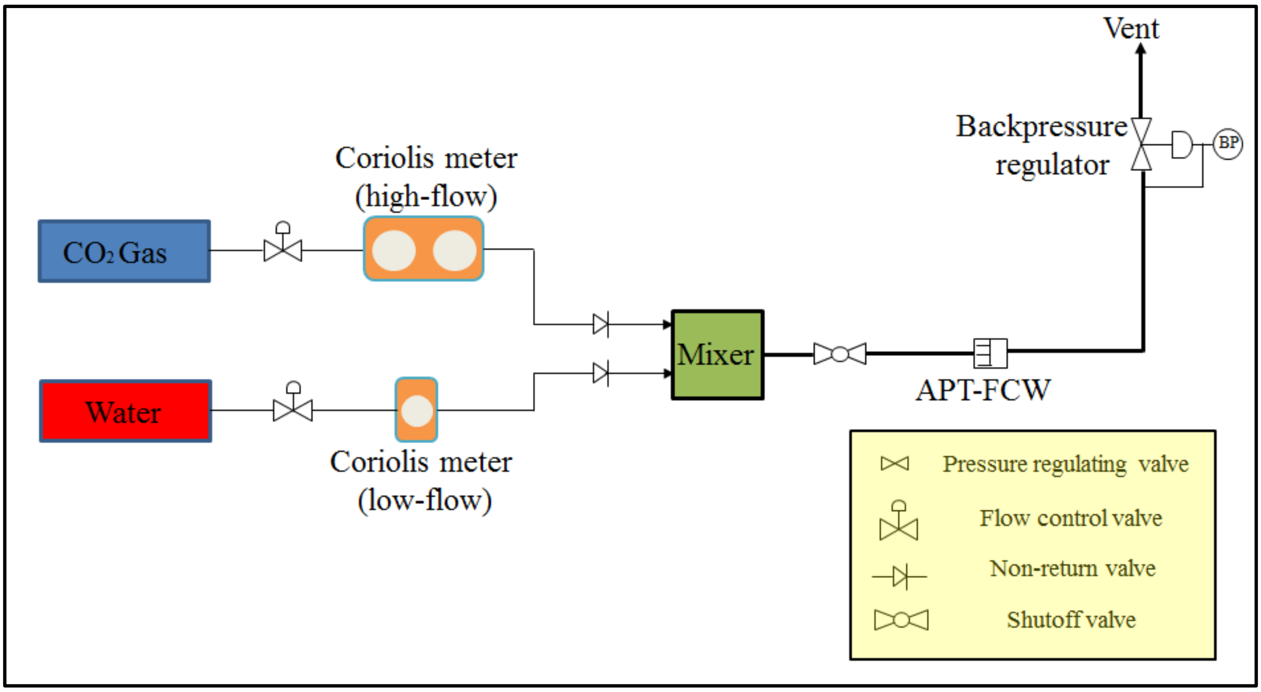


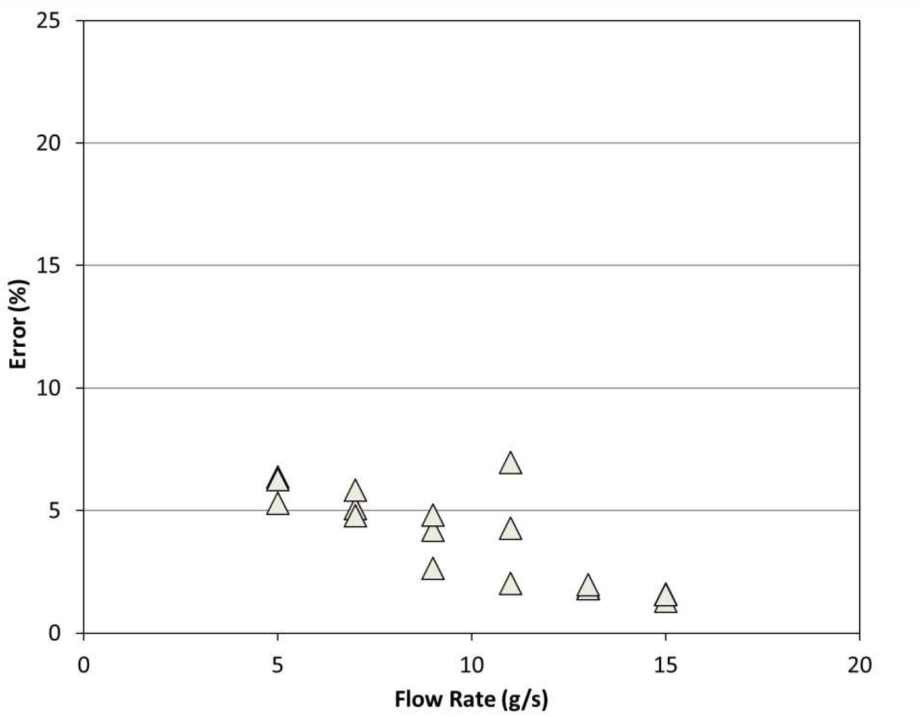
Fig. 3. Schematic of the experimental setup.

During the experiments the flow could be stopped at any time with a shut-off valve situated on the process line. The fluids were mixed by the mass fraction method. Combined total gas-liquid two-phase flow rates from 5 to 15 g/s with an increment of 2 g/s for liquid fractions 5, 10, 15 and 20% were tested for a batch size of around 700g using the standing start and stop batching procedure. Under wet-gas conditions, the maximum tested gas and water flow rates were 12 g/s and 3 g/s, respectively. To determine the over-read, the experimental procedure was carried out in two main sequences. First, the differential pressures (ΔP_g) for the test flow rate for dry gas was obtained when only the CO_2 gas flowed through the pipeline. The second sequence followed by introducing water into the process line at the desired mix ratios to obtain the wet differential pressures (ΔP_{wg}) and combined total flow rates. A dedicated PC was used to record the real-time data from the CMFs while two data loggers were used to collect and store other relevant metering information such as flow pressure and DP. The calculated flow rate and totalized mass of fluid through the APT-FCW were referenced against those of the upstream single-phase CO_2. The temperature of the mixture during experimental runs was around 20°C.

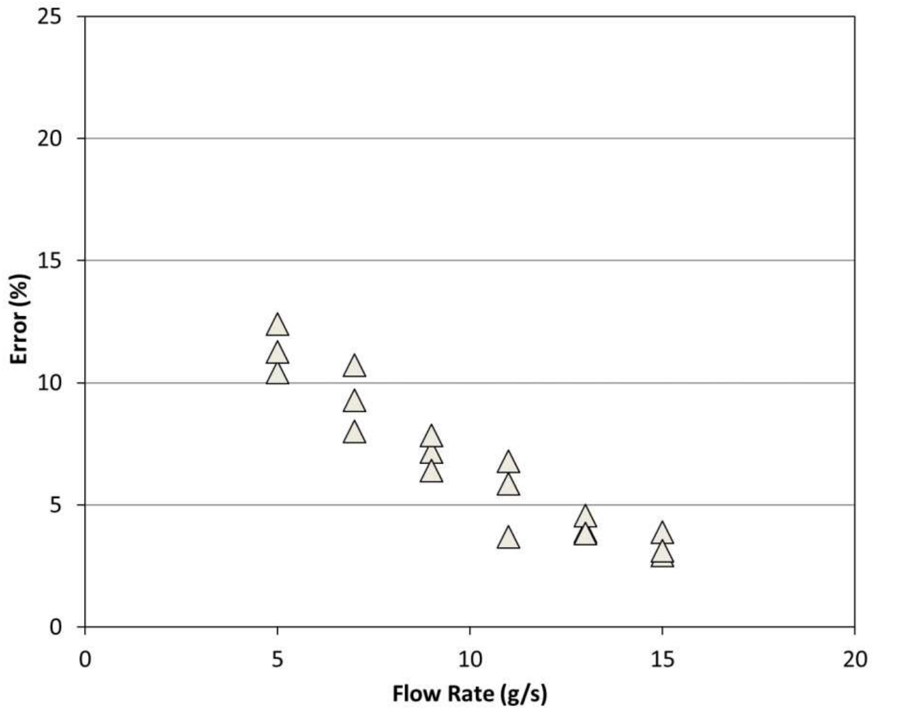
A sight glass installed on the flow rig showed that the flow pattern was mainly of stratified type for different flow velocity of the CO_2 gas and mass fraction of the liquid content. The uncertainties of the CMFs and APT-FCW based on single-phase CO_2 gas calibration characteristics are within ±1% and ±1.5%, respectively [15, 16]. The calibration procedure is traceable to a standard mass balancing system.

4. RESULTS AND DISCUSSION

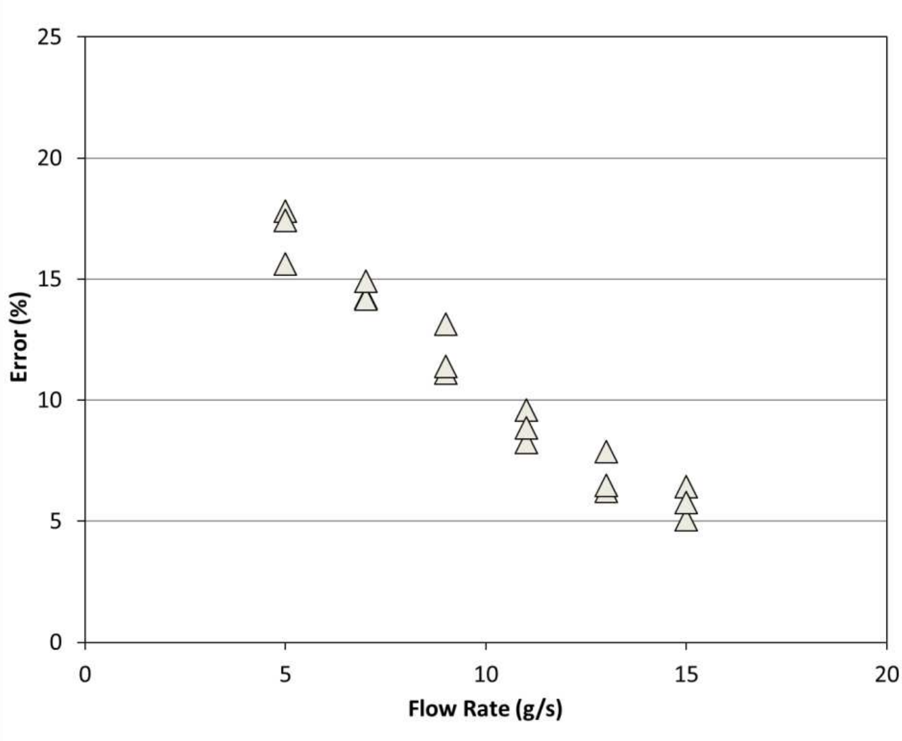
Fig. 4 shows the error in the totalized mass of the APT-FCW for different fractions of liquid fluid in the gas stream. Each test was repeated for at least three times under each condition. As expected, the error generally increases with the mass fraction of liquid in the mixture. The same set of data is plotted in Fig. 5 to present a collated and more composite comparison with the total mass recorded from the single-phase CMF gas data and the APT-FCW. The continuous drift of the mass error from the ±1% boundary for dry CO_2 gas is evident as the degree of wetness in the flow stream increases. Figs. 6 and 7 illustrate that, although the measurement error increases with the liquid fraction in the flow stream, it conversely reduces with the flow rate. During experimental runs, it was observed that water bubble entrainment in the sensing ports of the APT-FCW were higher at lower flow rates than at the higher end of the flow test range. As the flow rate was increased, the majority of these water bubbles were forced or flushed out of the sensing ports and back into the flow stream. Thus the measurement error is much lower at this region of the test range. This was also partly confirmed by physically inspecting the probe of the flow sensor. Fig. 8 shows the plot of the data from the solved over-read and Lockhart-Martinelli equations, which confirm the error behavioural pattern of the sensor detailed in Figs. 4 to 7 with respect to the mixture flow rate and the amount of liquid content in the mixture.



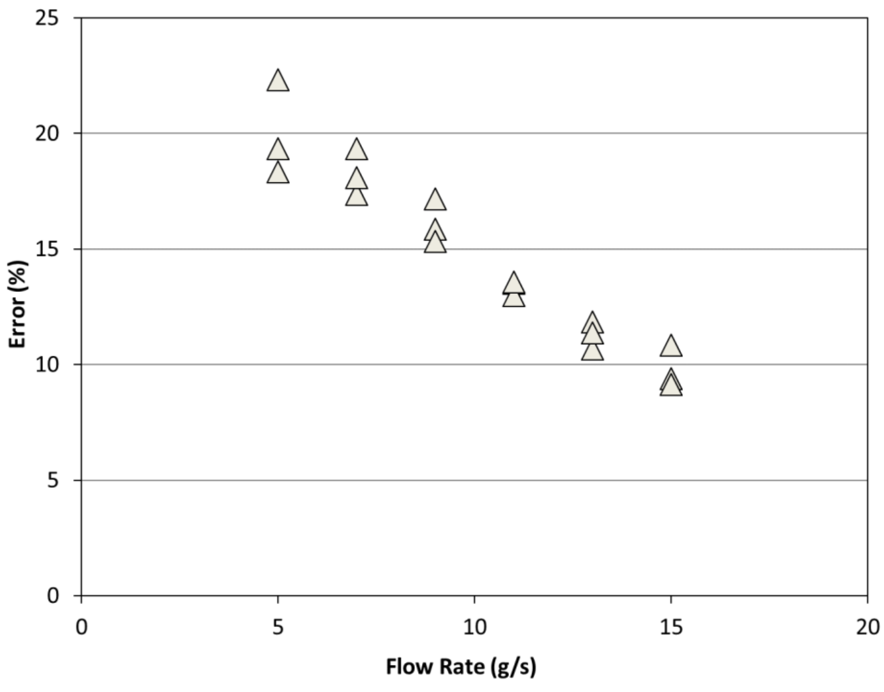
(a) Liquid fraction: 5%.



(b) Liquid fraction: 10%.



(c) Liquid fraction: 15%.



(d) Liquid fraction: 20%.

Fig. 4. Errors of the measured total mass for different liquid mass fractions.

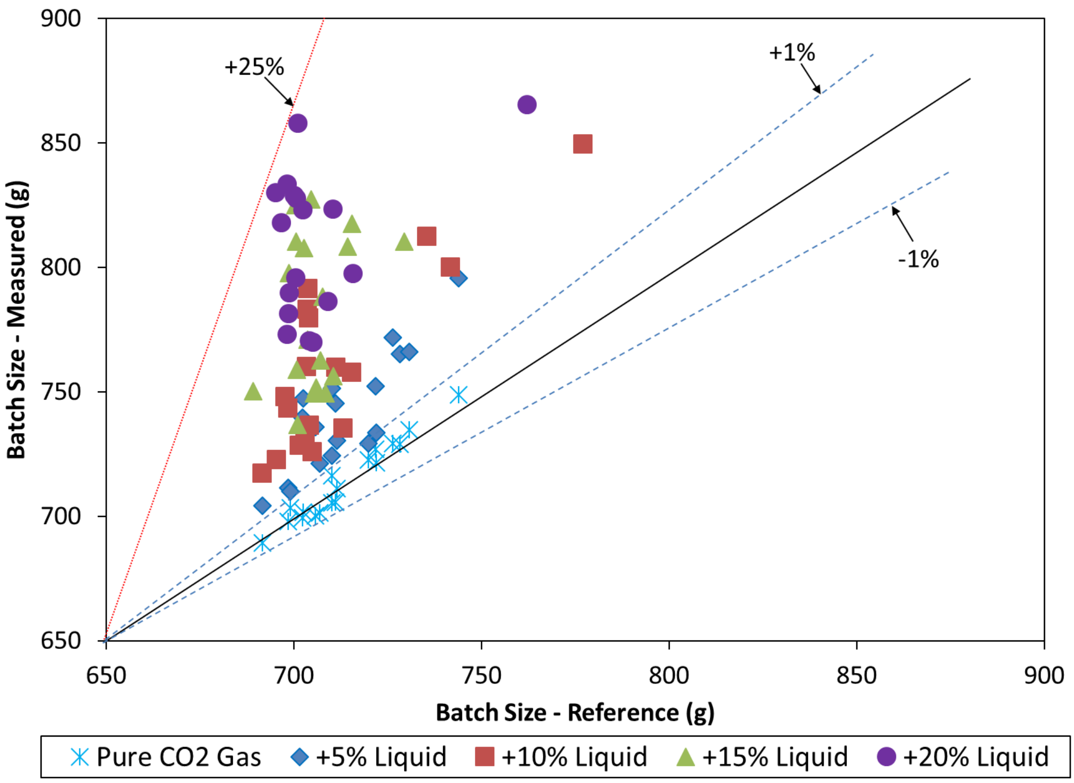


Fig. 5. Errors of the measured total mass of dry CO_2 vs. wet CO_2 gas.

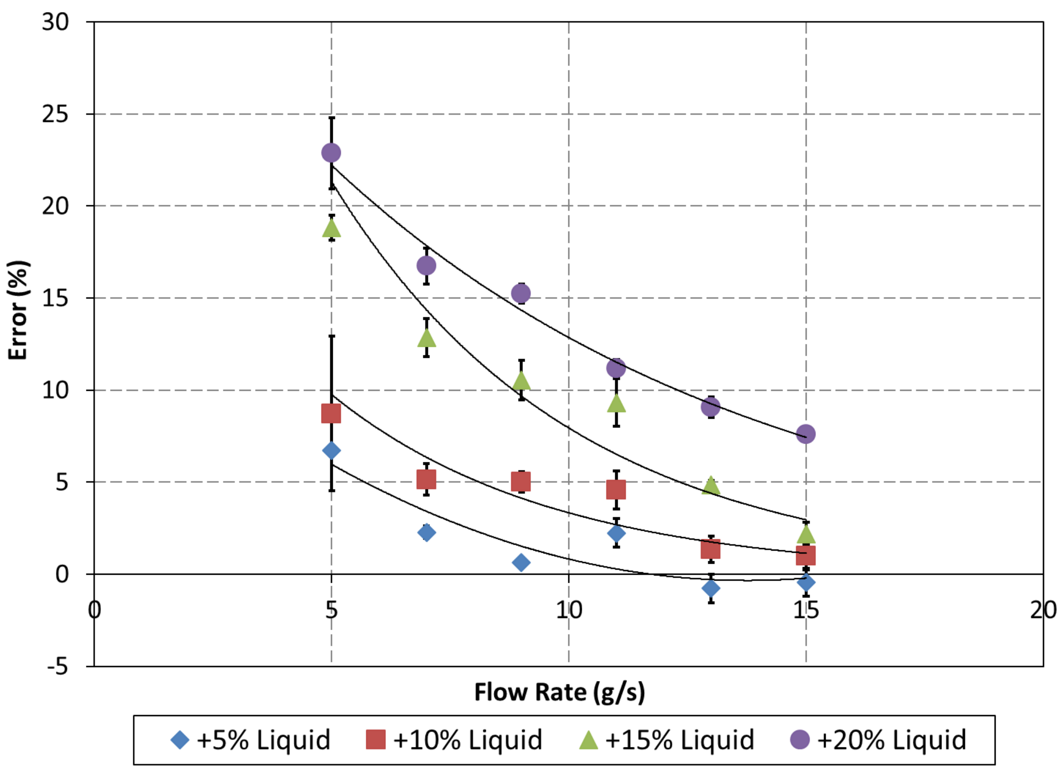


Fig. 6. Error of the mass flow rate for different liquid mass fractions.

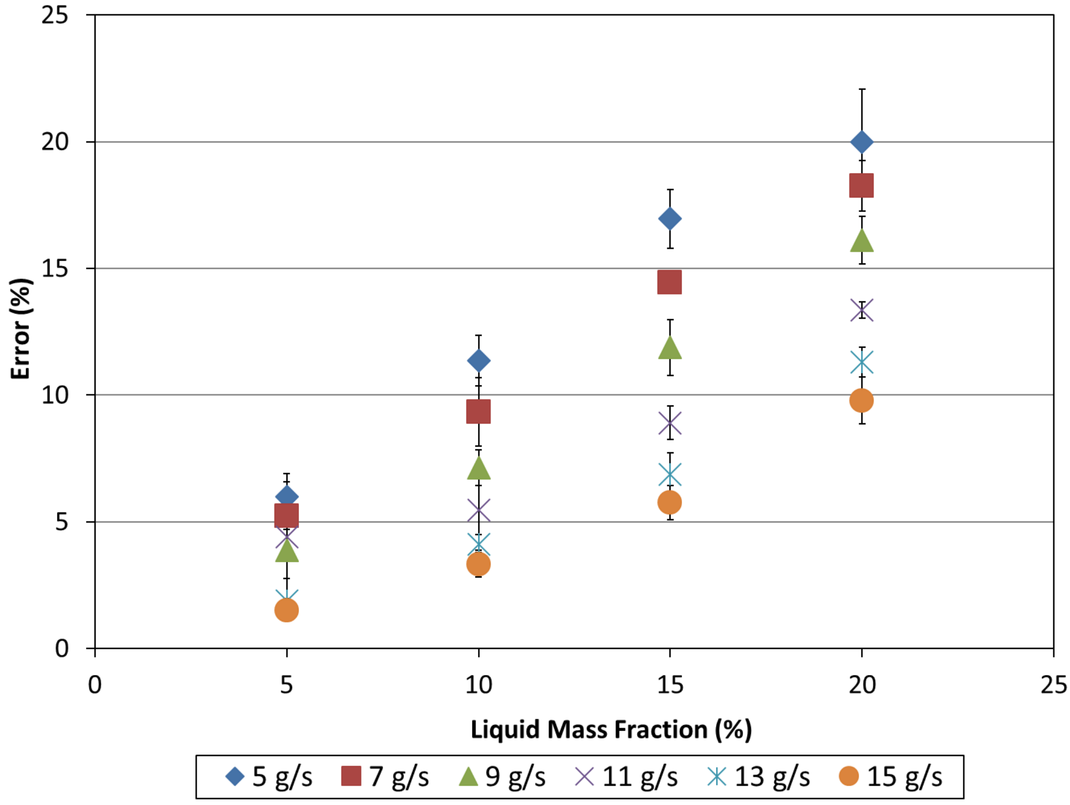


Fig. 7. Error of the mass flow rate as a function of liquid mass fraction.

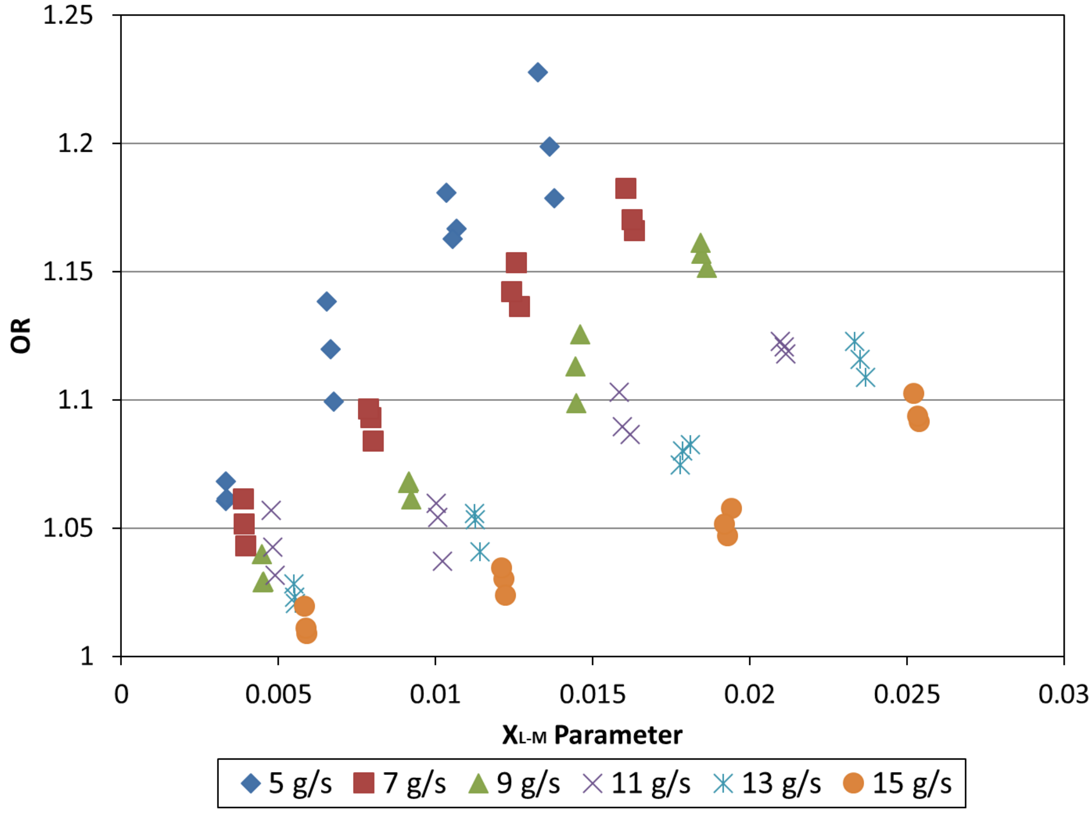


Fig. 8. Mass flow rate over-read vs. wetness of mixture.

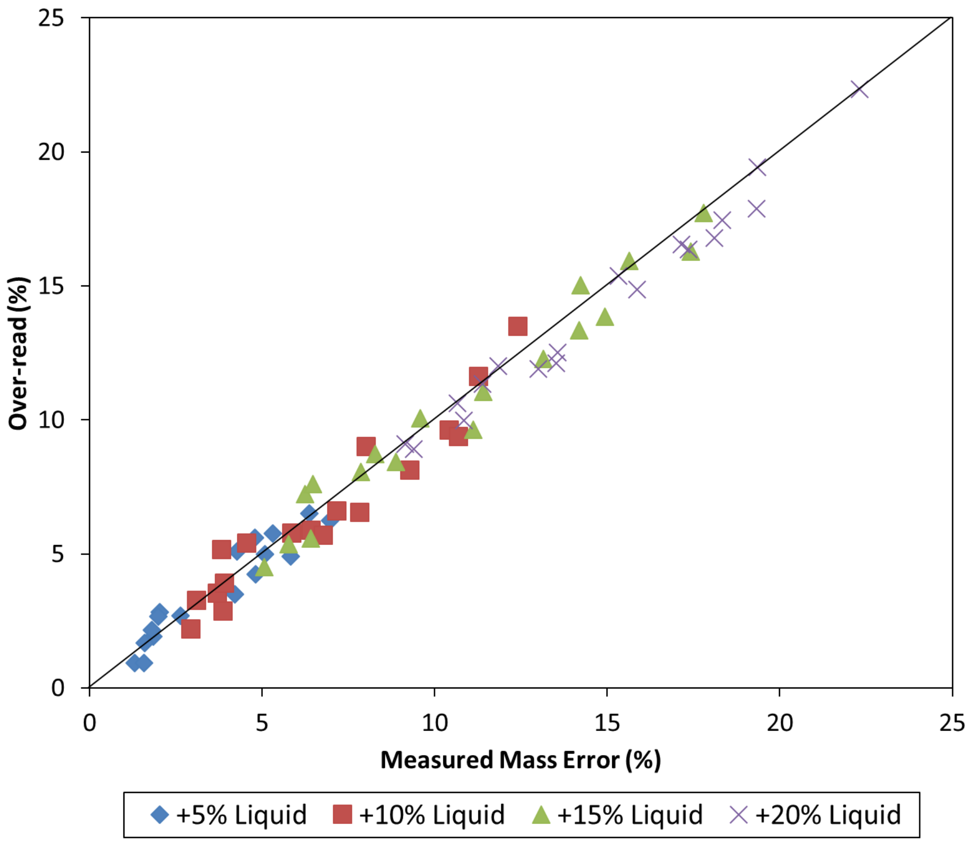


Fig. 9. APT-FCW over-read vs. total mass error.

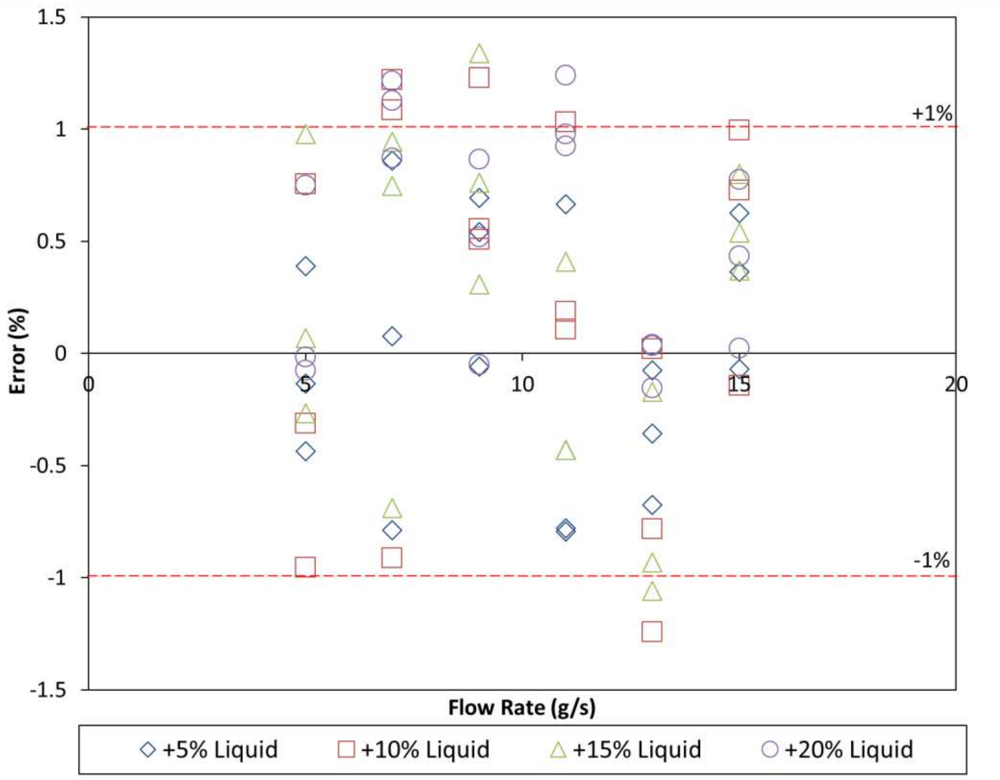


Fig. 10. Error of corrected DP over-read of all test data using the direct method.

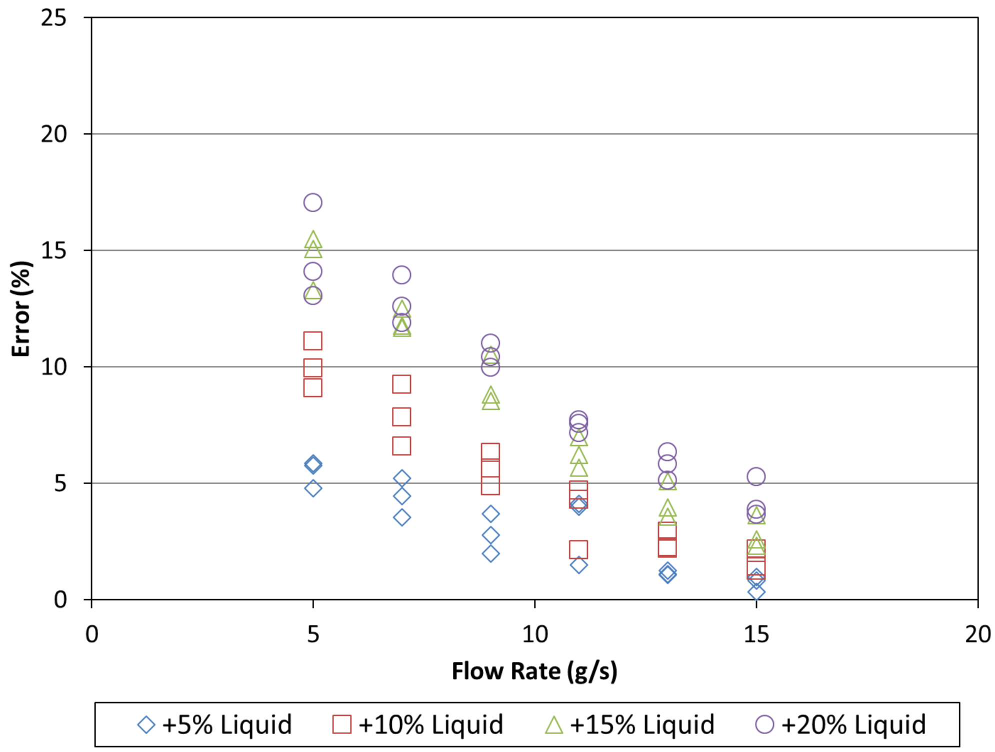


Fig. 11. Error of corrected DP over-read of all test data using the de Leeuw model.

In Fig. 9, notice how the over-read expression in terms of mass units strongly correlates with that of the calculated total mass error. It can therefore be concluded that the error deviation of the DP output under wet conditions is more or less or in general, considerably proportional to the meter's volumetric and mass flow errors. Finally, as can be seen in Fig. 10, when the correcting solution of Eqn. (6) was applied to the indicated DP readings obtained under wet flow conditions, around 90% of the entire data were corrected to within the original ±1% error calibration of the APT-FCW sensor for single-phase CO_2 characteristics. On the other hand, of all the other tested correlations, de Leeuw and the Homogeneous models both produced identical and the most noticeable correction, with a maximum error of around 17%. Fig. 11 shows the error of the corrected DP using the de Leeuw model. The Chisholm and Murdock correlation models offered little to no correction with maximum error of around 23%. In practice, with knowledge of the gas flow rate and wetness of the mixture, this correction procedure can be programmed into a "flow computer" to compute the actual flow rate of the dry CO_2 gas in real-time or as measurements are being taken. Other necessary parameters of the gas and liquid and other flow condition like densities, pressures, temperature etc., would need to be entered into the computer.

5. CONCLUSIONS

The effect of the presence of liquid fluid on the response of the APT-FCW flow sensor with reference to single-phase CO_2 gas calibration characteristics has been demonstrated in this paper. The APT-FCW gave an error of up to ±25%, for a liquid fraction of up to 20%. Aside from the amount of liquid content in the flow stream, water bubble entrainment in the ports of the sensor was confirmed to be responsible for larger errors at lower flow rates. For example, an error of around 6% at 5 g/s and 2% at 15 g/s was observed for a liquid fraction of 5%. As the flow rate increased, this flow obstruction appeared to be less severe, freeing up most of the ports and in turn affecting an error decline in the measurement results. With knowledge of the absolute gas flow rate and mixture wetness, most of the errors in the measurements can be corrected through appropriate simple and straightforward equations which are easily incorporated into computing processes in the flowmeters. The direct over-read correlation method corrected most of the errors from the CO_2-water mixture to within the original ±1% calibration boundary of the APT-FCW. The error corrections offered by other wet-gas correlation models were generally unacceptable (17~23%). With further study, a correlation model between the known wetness of the mixture and over-read can be developed specifically for the APT-FCW flow sensor. The compact and convenient flow sensing operation of the APT-FCW and its easily correctable wet-gas error proves that it can be developed into a reliable metering technology for CCS applications. Future work in this research area will focus on the analysis of the metrological performance of the flow sensor for pressurized liquid CO_2 flows.

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