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Technical Paper

Investigation of the transferability of calibration between alternative fluids for liquid and dense phase Carbon Dioxide Fiscal Flow Measurement

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1. INTRODUCTION

Carbon Capture and Storage (CCS) is a key technology to reduce Carbon Dioxide emissions. According to the IPCC [1], CCS deployment is critical to reduce carbon dioxide emissions and reach net-zero targets. The UK Government committing £1 billion for two CCS clusters to be in operation by the mid 2020s and a further two being deployed by 2030 [2], [3]. Globally the demand for CCS has been increasing, with the number of facilities in early or advanced stage development growing significantly since 2021, amounting to a near doubling of capture capacity[4].

However, current CCS capacity is negligible if compared with current global CO_2 emissions. The key challenge is to deploy CCS at the scale and pace required to timely mitigate the severity of climate change. Some countries will primarily rely on government subsidies to deploy CCS while others will primarily rely on private investments and the market. Either way the amount of CO_2 captured, transported, and stored will need to be accurately quantified, as this will underpin the financial transactions between the involved parties and will be needed to ensure compliance with regulatory requirements[5].

To meet this purposes, fiscal flow meters will be installed across the CCS chain and each of them will be required to comply with quality assurance requirements such as routine calibration. The technologies used in this application will likely mimic those currently in use in the oil, gas and water industries [5], [6]

A key gap in quality assurance is that currently there are no traceable liquid CO_2 calibration facilities anywhere around the world that can cover the flow rates, pressure and temperatures range required across the CCS chain[5]. However, there are several accredited water and oil calibration facilities around the world. An important question that arises is if flow meters can be calibrated in water or oil and used with liquid and dense phase CO_2.

To answer this question an experimental campaign was undertaken at TÜV SÜD National Engineering Laboratory (NEL), the UK designated institute for flow measurement. Different flow metering technologies were calibrated with water, oil and liquid and dense phase CO_2 and the transferability of calibration between these fluids was assessed. While a total of four flow meters were tested as part of this work, only the results of the Coriolis meter will be presented here. The results of this experimental assessment will be presented and based on them, recommendations on flow metering calibration strategy will be provided to the wider industry.

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2. EXPREIMENTAL SETUP

A transfer package containing one orifice meter, two ultrasonic clamp-on meters, one helical turbine meter and one Coriolis meter was assembled in series at NEL. The flow meter package included two Zanker type flow conditioners, one 8.5D upstream of the orifice plate and the other 15D downstream of the orifice and 8D upstream of the clamp-on ultrasonic meters.

The orifice plate had a nominal diameter ratio of β = 0.6, with an orifice diameter of 29.532 mm and the pipe internal diameter was 49.22 mm. The orifice plate and associated pipework was calibrated against the NEL water calibration facility's reference meters to determine the measured discharge coefficient. This calibrated discharge coefficient was then used in the calculation of the reported flow rate through the orifice. This meter was used as the reference flow meter for the reported results.

Two clamp-on ultrasonic meters and a helical turbine meter were also included in the transfer package but are not reported here.

Table 1 - Transfer Package Specification

Tag Number	Meter Type	Size	Manufacturer	Model
FT1	Orifice 0.6 Beta	2 inch	McMennon	Compliant with ISO 5167
FT4	Coriolis	1 inch	Emerson	CMF100M

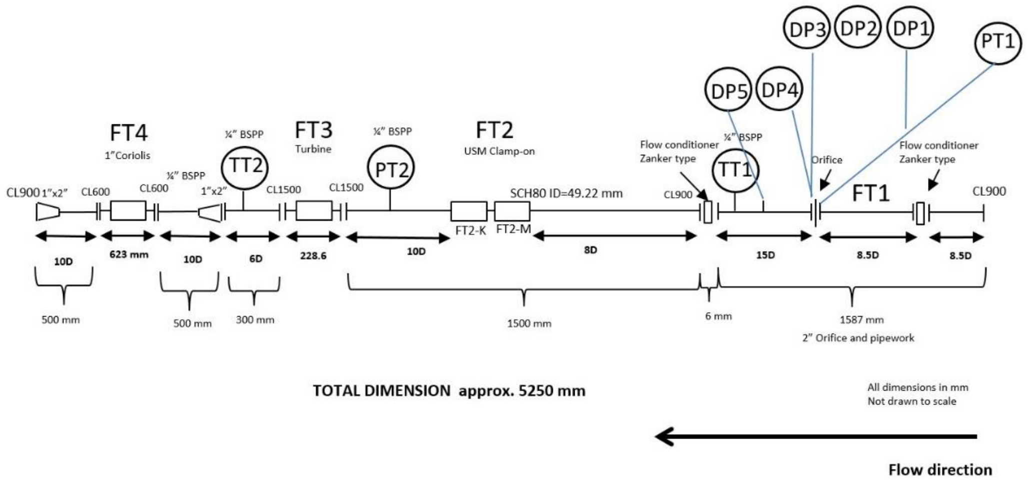

Figure 1 - Transfer Package Design Drawing

2.1. Experimental set-up and Test Procedure

The five flow meters were initially installed at the NEL's water calibration facility and calibrated against the facility reference master meters (Coriolis meters). The transfer package was then tested at NEL's Elevated Pressure and Temperature (EPAT) oil facility and at the Institute for Energy Technologies' carbon dioxide facility. The orifice meter was also tested at NEL's high pressure nitrogen facility to cover higher Reynolds number range than what achievable with water.

Due to the lack of traceable liquid CO_2 flow facilities in the world, the flow meter package was installed and tested at the Institute for Energy Technology's (IFE) FALCON liquid CO_2 flow facility in Kjeller, Norway. The package set-up, orientation and pipework remained the same between the tests at NEL and IFE.

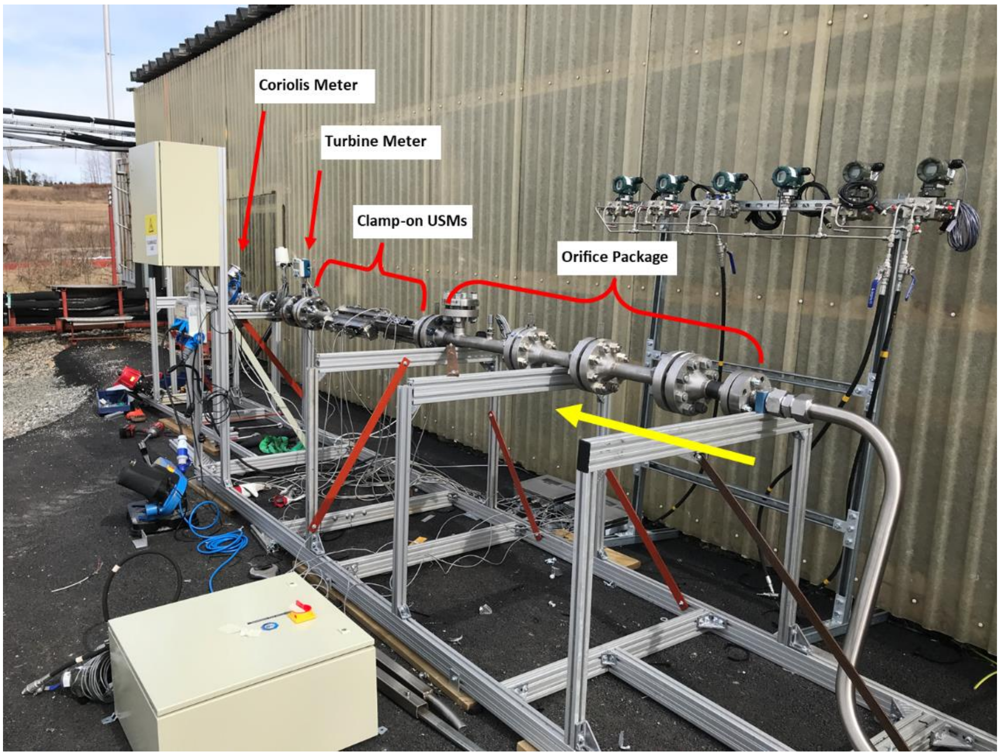

Figure 2 - Test Set-up in Liquid CO2 at IFE, Oslo

The calibration obtained in water for each meter were applied to the results obtained with oil (NEL), and liquid and dense phase CO_2 (IFE). The purpose of this is to investigate whether the calibration applied from the water tests is still valid in for use with CO_2.

For the Orifice meter this took the form of the ISO 5167 discharge coefficient curve fitted to the water data by an offset coefficient as follow:

$$C_{fitted} = C_{ISO} + 0.00507 \quad (1)$$

The pipe Reynolds (Re_D) range tested with water was $3x10^4$ to $1.5x10^5$. Tests to check the fitted discharge coefficient performance up to Re_D $1.7x10^6$ were conducted with nitrogen at 50 barg, see Figure 4. The orifice meter was used as the reference meter in the oil and CO_2 tests. The main reason is that no traceable master meters or primary standards were available at IFE for the CO_2 tests. In the absence of them the orifice meter was considered the best device to act as a stable reference meter given that its performance is irrespective of the fluid employed and mainly a function of the Reynolds number.

The Coriolis pulse measurements used the average calibrated K-Factor obtained in water (59.95 pulse/kg).

Prior to starting testing at each pressure and temperature conditions, both the orifice meter Differential Pressure Transmitters (DP) and the Coriolis meter were zeroed.

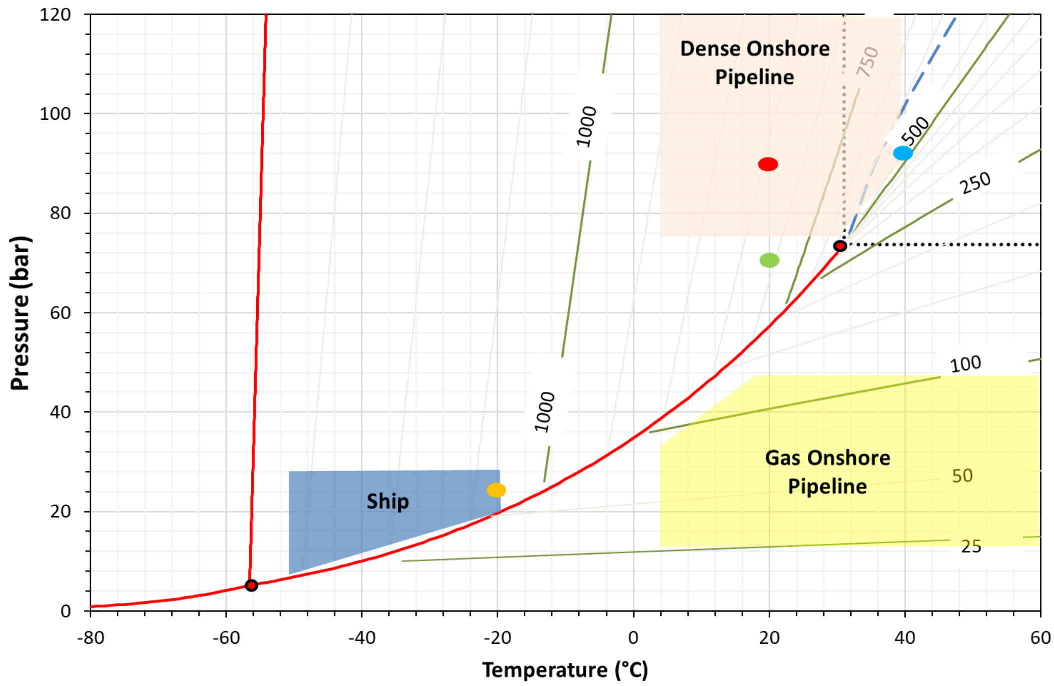

Figure 3 – Pure CO2 Phase Diagram with points showing location of each set of test conditions

IFE measured the composition of the CO_2 in the facility using both Gas Chromatography and Laser Spectrometry and reported a purity of 99.82 % by volume with 0.13 % Oxygen and the remaining containing trace amounts of methane (0.03 %) and water (0.02 %).

3. CALCULATIONS

The mass flow and volume flow through the orifice was calculated using the equation from ISO 5167-2 [7], [8]:

$$q_m = \frac{C_{fitted}}{\sqrt{1-\beta^4}}\,\varepsilon\,\frac{\pi}{4}d^2\sqrt{2\,\Delta p\,\rho_1} \tag{2}$$

where C_{fitted} is the ISO discharge coefficient fitted to the water data by an offset coefficient. The expansibility factor ε was calculated according to ISO 5167- 2:

$$\varepsilon = 1 - (0.351 + 0.256\beta^4 + 0.93\beta^8)(1 - \left(\frac{p_2}{p_1}\right)^{1/k}) \tag{3}$$

A pressure correction factor for the Coriolis meter was determined during the testing in the Elevated Pressure and Temperature Oil Facility at NEL. The resulting correction factor for flow measurement was applied to all the results for the Coriolis meter as follows:

$$E_{corrected} = E_{raw} - (-0.0192 * (P_{local} - P_{fcalibration})) \tag{4}$$

The error of the mass flow output from the Coriolis meter is reported in relative terms to the Orifice meter using the equation below.

$$E_{\%} = \frac{q_{Coriolis} - q_{Orifice}}{q_{Orifice}} * 100 \tag{5}$$

The density output from the 1-inch Coriolis meter was calibrated at the NEL Densitometer calibration facility and the following pressure and temperature corrections applied to the liquid and dense phase density measurements.

$$\rho_{Corrected} = \rho_{Measured} + (0.2845 * P_{absolute}) + 1.8734 \tag{6}$$

$$\rho_{Corrected} = \rho_{Measured} + (0.3033 * P_{absolute}) + 0.2557 \tag{7}$$

$$\rho_{Corrected} = \rho_{Measured} + (0.0655 * T) + 4.6907 \tag{8}$$

Equation (6) is applied to dense phase CO_2 measurements above the critical temperature, while equation (7) applies to dense phase CO_2 at 20° C, 70 & 90 bar, and equation (8) applies to liquid CO_2 at -20° C.

4. RESULTS

4.1. Reference Orifice Meter Calibration

A calibrated discharge coefficient was developed from the measured results taken during testing in the NEL Water, Elevated Pressure & Temperature Oil (EPAT) and High-Pressure Gas flow facilities. The Orifice Meter was calibrated between a Reynolds number range of 6.15×10^3 – 1.72×10^6 and the resulting measured discharge coefficient curve across the three calibration fluids was within ±0.2% of the calibrated fitted discharge coefficient. See Figure 4.

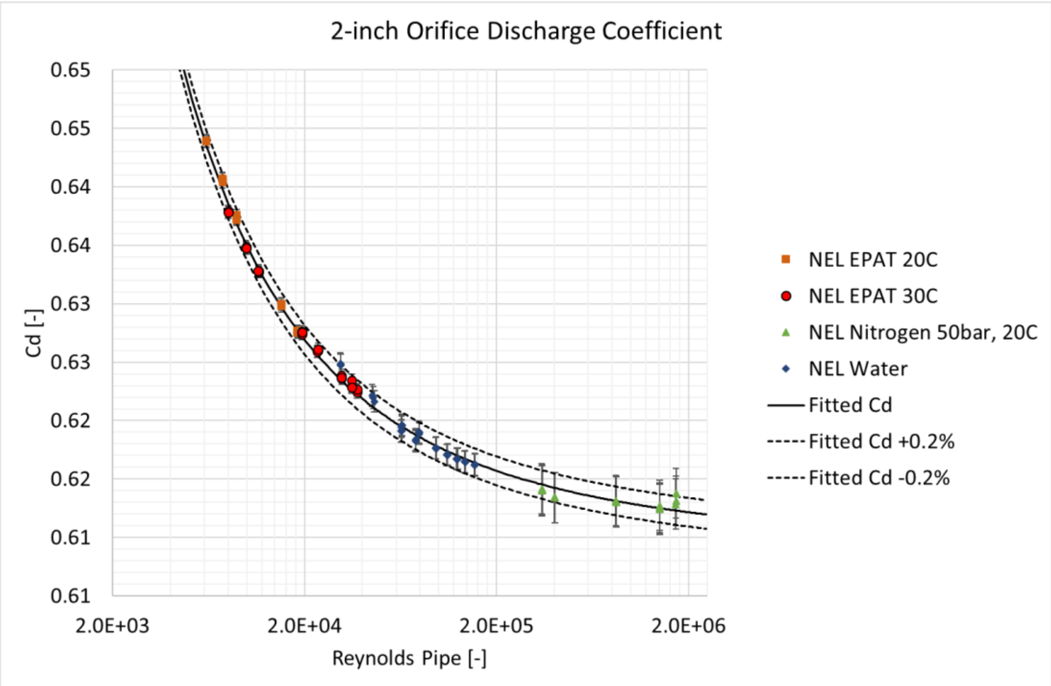

Figure 4 - 2-inch Orifice Discharge Coefficient Calibration Data

4.2. 1-inch Coriolis Meter Results

The Coriolis shows good agreement with the orifice meter for the water and oil results after the initial water calibration was applied. With the exception of the lowest flow rate in oil at 20° C, the error doesn't exceed ±0.08%, see Figure 5. This is within the uncertainty of both the Water and EPAT Oil facilities.

For the CO_2 test, the 1-inch Coriolis meter shows a positive bias to the orifice when the density used in the reference orifice meter calculations comes from the Coriolis density output. See Figure 5. Overall the agreement between Coriolis meter and orifice meter across all the CO_2 tested conditions is within ±0.35 %.

When instead the Span and Wagner EoS is used for the orifice density, the agreement between Coriolis and orifice gets worse, with the error in mass flow reaching a ±0.4 % limits. The striking difference when calculating the orifice density from EoS is the substantial shift in the Coriolis results for dense phase CO_2 at 40° C (i.e. supercritical CO_2). Further investigation is required to investigate this difference in results.

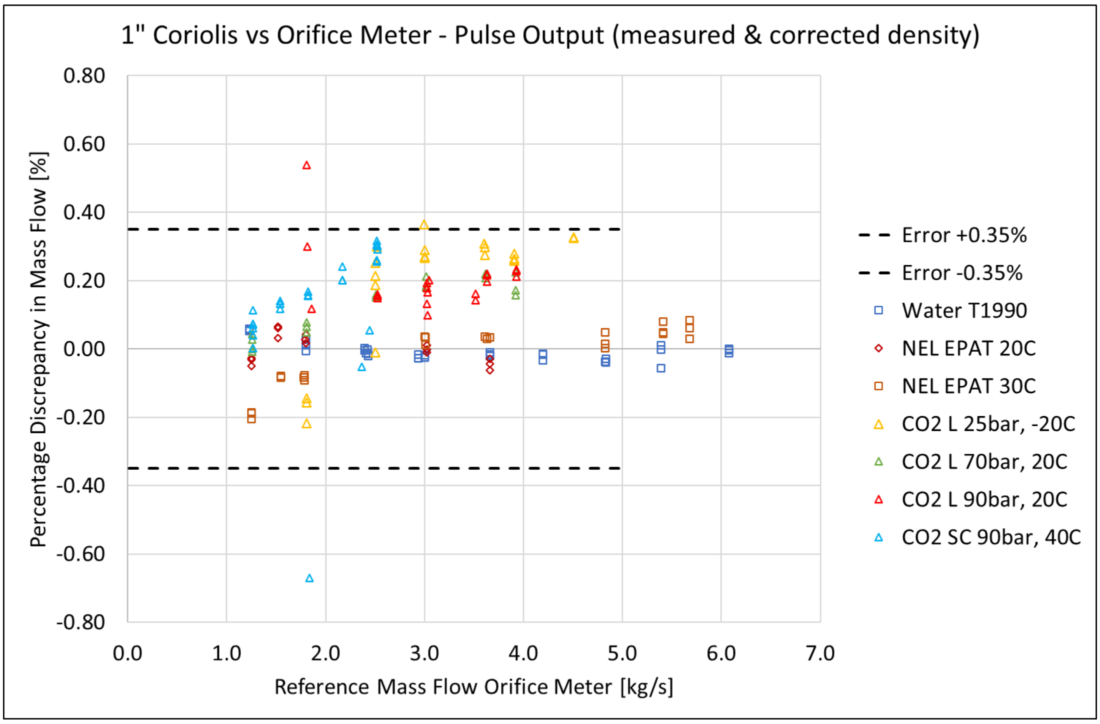

Figure 5 - 1-inch Coriolis meter results. Measured, corrected Density was used in the calculation of mass flow for the reference orifice meter.

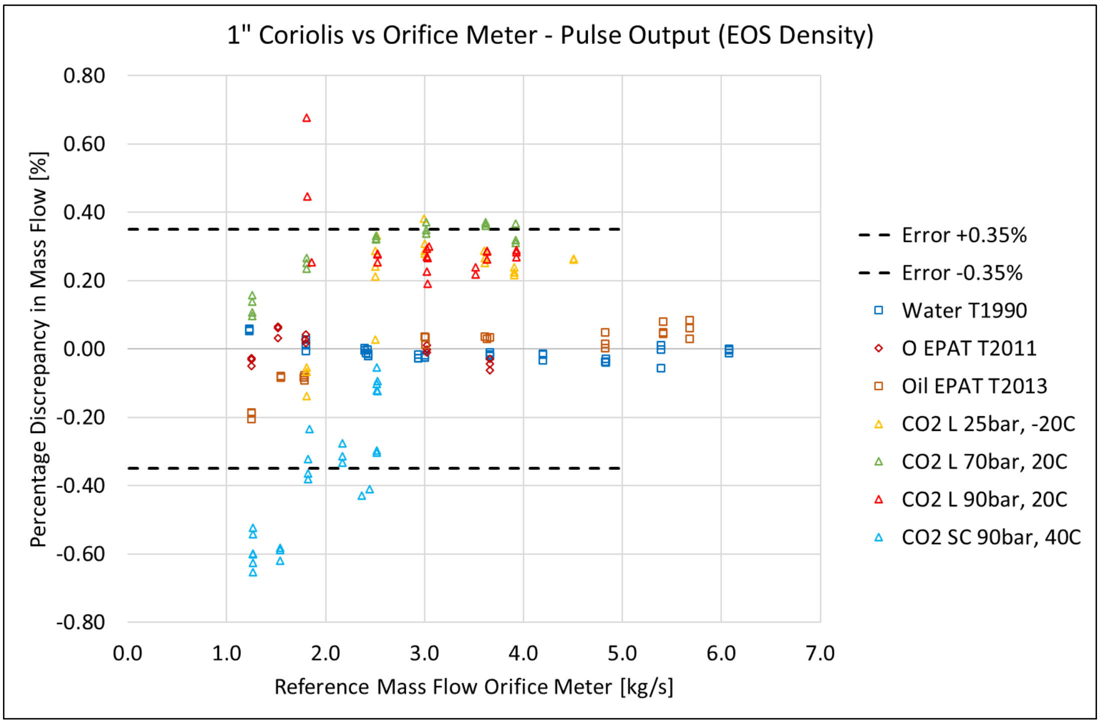

Figure 6 - 1-inch Coriolis meter results. EOS Density was used in the calculation of mass flow for the reference orifice meter.

5. CONCLUSIONS

The purpose of this experimental work was to investigate whether a Coriolis meter could be calibrated in water for use in liquid and dense phase CO_2 as part of a wider experimental campaign to investigate the same question across four separate flow meters. The remaining three meters are not presented in this paper, but results will be presented in future publications.

Tests were run at TÜV SÜD National Engineering Laboratory (NEL) with water and oil. Tests with CO_2 were undertaken at the Institute for Energy Technology's (IFE) FALCON liquid CO_2 flow facility in Kjeller, Norway. No traceable master meters or primary standards were available at IFE for CO_2. In the absence of reference flow standards, an orifice meter was calibrated at NEL with water and with nitrogen and used as the reference meter to conduct a relative assessment.

The discrepancy between the Coriolis and orifice meter with water and oil is within ±0.08 %. For liquid and dense phase CO_2, the agreement is within 0.35 % (when the density in input to the orifice meter is measured directly with the Coriolis) which is approximately within the expected uncertainty of the orifice meter. As such, firm conclusions on the transferability of calibration cannot be drawn until a suitable reference standard with lower uncertainty is built, and further research is conducted testing multiple CO_2 stream mixtures composition, and multiple meters sizes from different manufactures. NEL is currently building a primary standard facility and is planning test work with CO_2 mixtures as part of an EU funded project called "A European Network of Research Infrastructures for CO2 Transport and Injection" (ENCASE).

For the time being, the presented results suggest to include an uncertainty source of approximately ±0.35 % in the meter uncertainty budget to account for the transferability of calibration from water to CO_2. However, it should be noted that to draw final conclusions further tests are necessary covering additional meter sizes from multiple manufacturers, additional flow rates and test conditions.

6. NOTATION

β	Ratio of the orifice diameter to pipe diameter
d	Diameter of orifice (m^2)
C	Discharge Coefficient of the Orifice
Re_D	Reynolds Number at the pipe
q	Mass flow rate (kg/s)
ΔP	Differential Pressure over the Orifice (Pa)
P	Static Pressure
ε	Expansibility Factor
ρ	Fluid density
k	Isentropic Exponent
E	Percentage error (%)
T	Fluid temperature (°C)

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8. REFERENCES

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