ORIFICE PLATE PRESSURE LOSS RATIO: THEORETICAL WORK IN COMPRESSIBLE FLOW AND EXPERIMENTAL WORK IN CO_2

Michael Reader-Harris and David Addison
TUV SUD NEL

Julian Barnett and Ketan Mistry
National Grid

SUMMARY

An 8” (200 mm) nominal diameter orifice plate assembly with a nominal diameter ratio, β, of 0.4 was tested in gaseous phase carbon dioxide (CO_2). The assembly had been calibrated in water using the TUV SUD NEL water flow test facilities at East Kilbride in Scotland. The orifice plate assembly incorporated flange tappings, with additional downstream tappings used for measurement of pressure loss ratio.

The test loop was filled with nitrogen, evacuated and then filled with CO_2 up to a pressure of 20 barg giving an estimated composition of 99.6% CO_2 by mol. Testing was carried out at 20 barg and 15 barg with additional test points at 12 barg.

Data on pressure loss ratio was collected from the orifice plate.

A correlation for pressure loss ratio in gas based on theory has been obtained, which deviates from the experimental data by only 0.0008, but further work with different orifice plate diameter ratios, pipe sizes and gases is required to prove the correlation.

1 INTRODUCTION

The tests were carried out in the TUV SUD NEL gas flow calibration loop. This calibration loop is normally configured for the calibration and testing of dry- and wet-gas flowmeters using nitrogen as the test gas and, for wet gas testing, water and/or kerosene as the liquid. The loop is constructed to operate at pressures up to 60 barg. Test meters are normally tested using a reference ultrasonic meter which, like all the other instrumentation, is calibrated and traceable to national standards.

2 METER, TEST INSTALLATION AND INSTRUMENTATION

2.1 NEL Orifice plate meter

An 8” (200 mm) nominal diameter orifice plate meter was tested. The orifice plate had a nominal diameter ratio, β, of 0.4. The orifice diameter was measured, at 20 °C, as 81.011 mm and the pipe internal diameter as 202.56 mm.

The plate and installation were compliant with ISO 51672:2003. Flange tappings were utilised for the measurements being reported. The test section had 6.5 m (> 30 D) of straight unrestricted upstream pipework and 2.5 m (13 D) of straight downstream pipework. An additional pressure tapping had been fitted 6 D downstream of the plate to be used for the diagnostic testing.

The orifice and associated pipework had previously been calibrated in water to give a measured discharge coefficient. This measured discharge coefficient provided a correction to the theoretical discharge coefficient at the Reynolds numbers used in gaseous phase CO_2 testing conducted. The calibration data and fitted curve are given in Figure 1, where the Reader-Harris/Gallagher (1998) Equation is shown together with a parallel equation based on the water calibration extrapolated to the Reynolds numbers for this gas test programme:

$$C = 0.59921 + 0.00087\left(\frac{10^6}{Re_D}\right)^{0.5} \qquad (1)$$

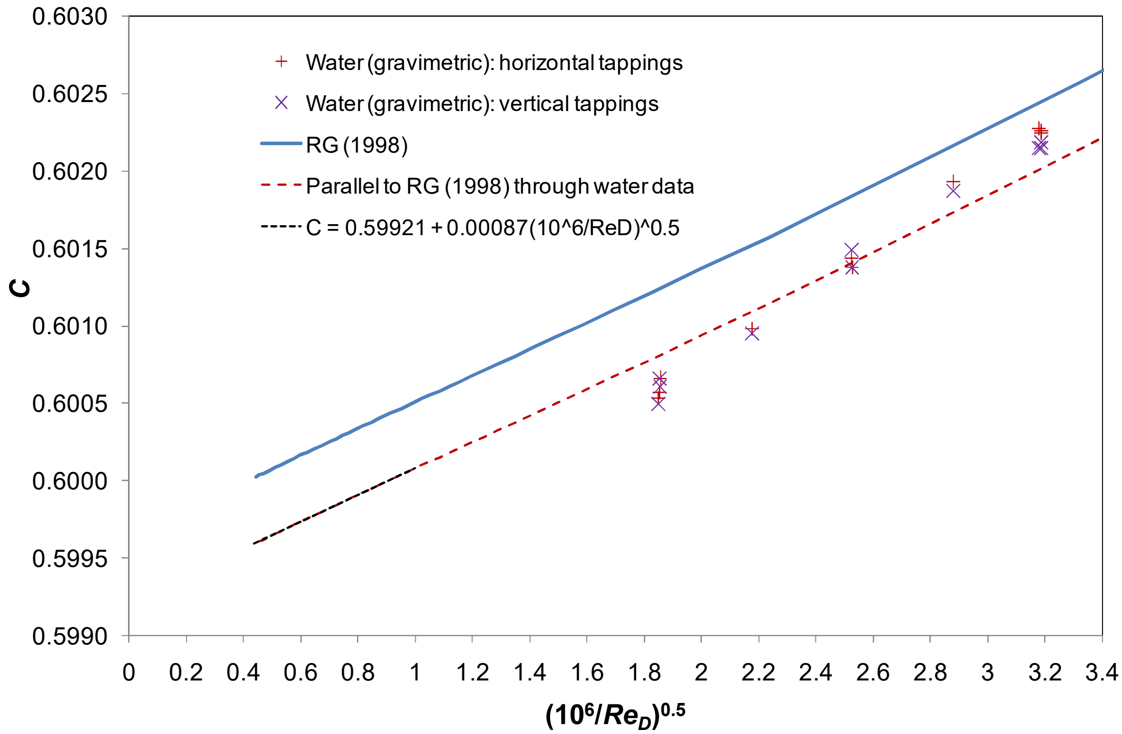

Figure 1 Discharge coefficient of the β = 0.4 orifice plate tested (RG (1998) is the Reader-Harris/Gallagher (1998) equation in 5.3.2.1 of ISO 5167-2:2003)

The flow calibration loop is shown in Figure 2.

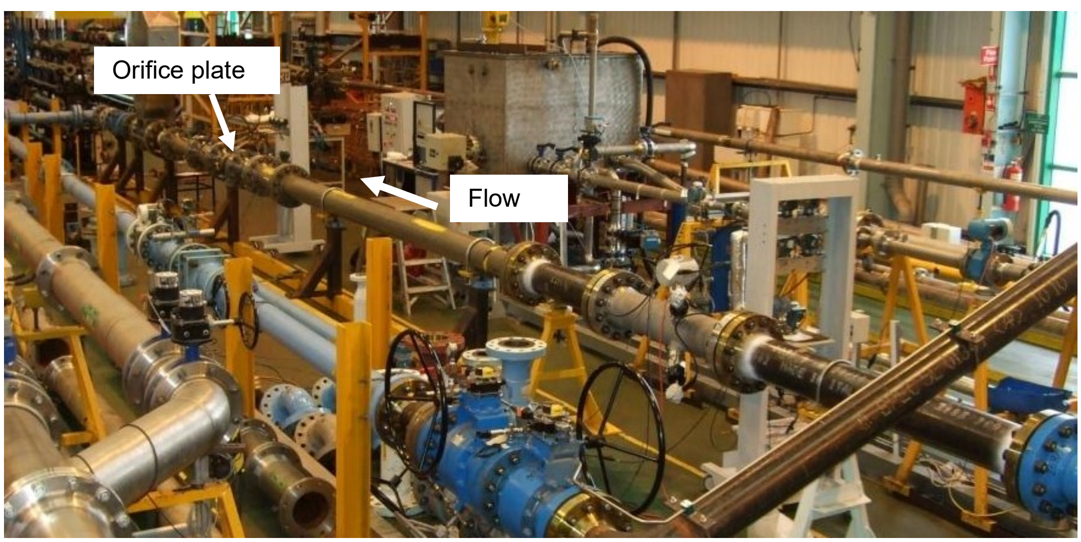

Figure 2 Installation of the orifice plate meter

2.2 Calculations

The properties of CO_2 were calculated from pressure, temperature and composition using the REFPROP [1] software package, which was verified by comparison with the TUV SUD NEL PPDS (Physical Properties Data Service) [2] properties package (see also Appendix A). For the purposes of the calculations, 100% CO_2 has been assumed rather than 99.6% concentration: this has a negligible effect on the results presented here.

The primary calculated property is density, which was calculated from the measured pressure, temperature and composition. This allows the calculation of mass flow from the orifice plate readings.

Viscosity, isentropic exponent and Joule-Thomson coefficient were also calculated and used in the orifice plate calculation.

Two additional differential pressure measurements were taken from the orifice plate: pressure loss and pressure recovery.

The orifice meter temperature was measured 8*D* downstream of the plate, and the Joule-Thomson correction was applied to provide the upstream temperature for the calculated density. The static pressure was measured at the upstream flange tapping.

2.3 Filling and operating the Loop

The loop was prepared for CO_2 following a defined procedure.

Air was diluted and removed by pressurising the rig with nitrogen, circulating and venting to atmosphere. The rig was then evacuated with a nitrogen purge at 100 mbara to remove the last traces of air and water vapour. Finally, the rig was evacuated to a pressure of 60 mbara. The flow calibration loop was then filled with CO_2 to the required pressure. Subsequently CO_2 was added or vented to obtain the required pressure for testing.

It was calculated that, using this method, the CO_2 should have a concentration of approximately 99.6% with nitrogen. This concentration was estimated from the absolute pressure in the flow loop when evacuated, the pressure when filled, the use of REFPROP's equations of state and assuming a constant rig volume and temperature. For flow testing it is not required to estimate the concentrations of other possible minor materials.

Tests were carried out at nominally 20 barg and 15 barg. In addition, an additional test over a limited number of flowrates was carried out at nominally 12 barg.

3 ORIFICE PLATE PRESSURE LOSS RATIO

3.1 Introduction

In any differential pressure flowmeter, the upstream pressure is reduced as the flow passes through the throat of the device, giving a differential pressure which is proportional to the square of the flowrate. The pressure then recovers a proportion of the differential pressure further downstream.

The pressure loss ratio is required for the design of orifice metering systems; the measured pressure loss ratio (see 3.3) is used in the orifice meter validation system developed by Steven of DP Diagnostics [3-7].

3.2 Theoretical work

The theory and practical testing in incompressible flow have been explored and reported in [8] and [9]. In compressible flow the pressure loss calculations are slightly different from those in [8] and are given below. The calculation in incompressible flow was first undertaken by Urner [10].

The momentum theorem is obtained by integrating the equation of motion over a fixed volume so that:

$$\rho \frac{Du_i}{Dt} = \rho F_i + \frac{\partial \sigma_{ij}}{\partial x_j}, \tag{2}$$

where ρ is the density, u_i the velocity in the x_i-direction, F_i the body force, σ_{ij} the stress tensor and *D/Dt* the derivative following the motion of the fluid, becomes, on expanding the derivative following the motion of the fluid and using mass conservation and the divergence theorem,

$$\iiint_V \frac{\partial(u_i \rho)}{\partial t} dV = -\iint_A \rho u_i u_j n_j dA + \iiint_V F_i \rho dV + \iint_A \sigma_{ij} n_j dA \tag{3}$$

where the fixed volume V is bounded by surface A.

The stress tensor consists of two terms: the pressure term is sufficient for the approximation here; so $\sigma_{ij} = -p\delta_{ij}$. The flow is steady and the body force (gravity) makes a contribution to the pressure that will make no contribution to the pressure loss.

Equation (3) is applied to the volume marked V on Figure 3.

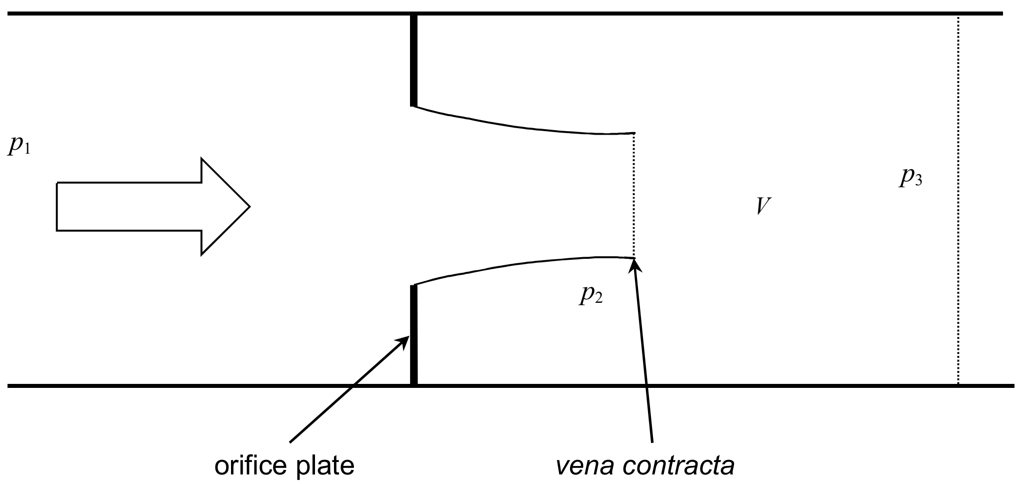

Figure 3 Flow through an orifice plate

Then, assuming that the pressure has the same value on the back of the orifice plate, on the edge of the orifice jet as far as the *vena contracta* and at the *vena contracta*, and using the divergence theorem:

$$0 = \rho_2 A_c u_c^2 - \rho_3 A_p u_3^2 - p_3 A_p + p_2 A_p \tag{4}$$

where A_p and A_c are the area of the pipe and the *vena contracta* respectively, u_c is the mean velocity at the *vena contracta*, p_2 and ρ_2 are the pressure and density downstream of the orifice plate, and p_3, ρ_3 and u_3 are the pressure, density and mean velocity respectively around 6*D* downstream of the orifice plate.

In practice it would be desirable to include frictional pressure loss. Using the estimate in [9], which corresponds to a loss due to a pipe of length 4.5β *D* of friction factor λ = 0.0125:

$$p_3 = \rho_2 u_c^2 \frac{A_c}{A_p} - \rho_3 u_3^2 + p_2 - 0.05625\beta \tfrac{1}{2} \rho_3 u_3^2 . \tag{5}$$

The flow is isentropic from a tapping point around 1*D* upstream to the throat. So:

$$\rho_2 = \rho_1 \left(\frac{p_2}{p_1} \right)^{1/\kappa}, \tag{6}$$

where p_1 and ρ_1 are the pressure and density around 1*D* upstream of the orifice plate.

Bernoulli's Theorem applies to the isentropic flow between the upstream 1*D* location and the *vena contracta*. In this case (see, e.g., equation (1.2) of [11]):

$$\frac{\kappa}{\kappa-1}\frac{p_1}{\rho_1}+\frac{1}{2}u_1^2=\frac{\kappa}{\kappa-1}\frac{p_2}{\rho_2}+\frac{1}{2}u_c^2 , \tag{7}$$

where u_1 is the mean velocity around 1*D* upstream of the orifice plate, and κ is the isentropic exponent.

The orifice discharge-coefficient equation (equation (1) of ISO 5167-2:2003) can be used to determine u_1:

$$u_1=\frac{\beta^2 C\varepsilon}{\sqrt{1-\beta^4}}\sqrt{\frac{2(p_1-p_2)}{\rho_1}} , \tag{8}$$

where C is the discharge coefficient using a tapping 1*D* upstream and at the location downstream where p_2 is measured and ε the expansibility factor.

Mass is conserved; so:

$$A_p\rho_1 u_1 = A_c\rho_2 u_c = A_p\rho_3 u_3 . \tag{9}$$

Following [9] the downstream pressure location for determination of p_2 (and hence C) was taken as 0.125*D* downstream of the plate (it has to be between the downstream corner and the *vena contracta*). It is now required to solve equations (5) to (9), but, whereas for incompressible flow a closed-form solution was found to the equivalent set of equations, here no closed-form solution was found. Although there is no closed-form solution to the equations, solutions can be obtained by iteration.

In practice tappings are not at 1*D* upstream and 0.125*D* downstream of the orifice plate (most commonly flange tappings are used as they were used for the data collected here); so it is necessary to calculate the difference between p_1 and the pressure at the upstream tapping and between p_2 and the pressure at the downstream tapping using the Reader-Harris/Gallagher (1998) Equation as in [8] and [9]. Then, using equations (5) to (9), the equations for the effect of different tapping locations and physical property data, the predicted values of the pressure loss ratio, using the orifice plate meter, were obtained and are shown in Figure 4. They are on average 0.0008 (i.e. 0.1%) below the measured values.

It is desirable to have an equation for the predicted pressure loss ratio for all gases, diameter ratios and tapping positions. So, although at present only one set of experimental compressible data in one fluid has been obtained, the pressure loss ratio was calculated for the following cases:

- β = 0.2, 0.4, 0.6 and 0.75
- Δp = 50, 100, 200, 500, 1000 mbar
- p = 4, 13.3 and 22 bar for CO_2 and p = 4, 15 and 60 bar for nitrogen
- 8" (200 mm) flange tappings

After considerable work it was found that these calculated values are fitted by the following equation with a standard deviation of 0.00021:

$$\frac{\Delta\varpi_{meas}}{\Delta p_{flange}} = \frac{\frac{p_{rise}}{\Delta p_{DandP}} + \frac{\sqrt{1-\beta^4(1-C_{DandP}{}^2)} - C_{DandP}\beta^2}{\sqrt{1-\beta^4(1-C_{DandP}{}^2)} + C_{DandP}\beta^2}}{1 + \frac{p_{rise}}{\Delta p_{DandP}} - \frac{\Delta p_{fdowntoP}}{\Delta p_{DandP}}} + \frac{0.05625\beta^5 C_{DandP}{}^2\varepsilon^2}{1-\beta^4} + 0.52(1-\varepsilon)\kappa\beta^{2.2} \tag{10a}$$

$$\frac{p_{rise}}{\Delta p_{DandP}} = \frac{2}{C_{DandP}}\frac{14.78}{14.30}\left(0.123e^{-7L_1} - 0.080e^{-10L_1} - 0.00011\right)\frac{\beta^4}{1-\beta^4} \tag{10b}$$

$$\frac{\Delta p_{fdowntoP}}{\Delta p_{DtoP}} = \frac{2}{C_{DandP}} 0.031\left(M'_{2P} - 0.8\times M'_{2P}{}^{1.1} - (M'_2 - 0.8\times M'_2{}^{1.1})\right)\beta^{1.3}, \tag{10c}$$

where C_{DandP} is determined from the Reader-Harris/Gallagher (1998) Equation with L_1 = 1 and L_2' = 0.125. In equations (10b) and (10c), L_1 and M_2' are based on the actual tapping positions and $M_2{}'_{P}$ on L_2' = 0.125. Equation (10) is shown on Figure 4.

Equation (10) is equation (2) of [9] with the addition of the final term in (10a) and the change in the penultimate term in (10a) to account for compressibility. It may be noted that the Joule-Thomson coefficient does not appear in these equations.

Equation (10) was tested by using calculated values with an ideal gas (Joule-Thomson coefficient equal to 0):

- β = 0.2, 0.4, 0.6 and 0.75
- Δp = 50, 100, 200, 500, 1000 mbar
- κ = 1.2, 1.4 and 1.67
- p = 4, 13.3, 22 and 60 bar
- 100 mm, 200 mm and 400 mm flange tappings

The standard deviation was 0.00024, very similar to the value with the two real gases.

3.3 Experimental work

For the testing of the orifice plate in CO_2 gaseous phase flow, three differential pressures were recorded, and the results analysed. The following three differential pressures were measured:

1. the differential pressure: from the upstream flange tapping to the downstream flange tapping, ΔP.
2. the measured pressure loss: from the upstream flange tapping to 6*D* downstream of the orifice plate, PL (note that the actual pressure loss may be different).
3. the measured pressure recovery from the downstream flange tapping to 6*D* downstream of the orifice plate, PR.

These three measured differential pressures are used in the orifice meter validation system developed by Steven of DP Diagnostics [3-7].

The measured (apparent) pressure loss ratio, PLR (=PL/ΔP) and the value of PLR deduced from the pressure recovery (=1-PR/ΔP) are shown in Figure 4. Data with PR < 15 mbar are omitted as it was found that the scatter increased for smaller values of PR. Measured values in water [9] are also shown. Equation (2) from [9], the correlation for incompressible flow, is also shown.

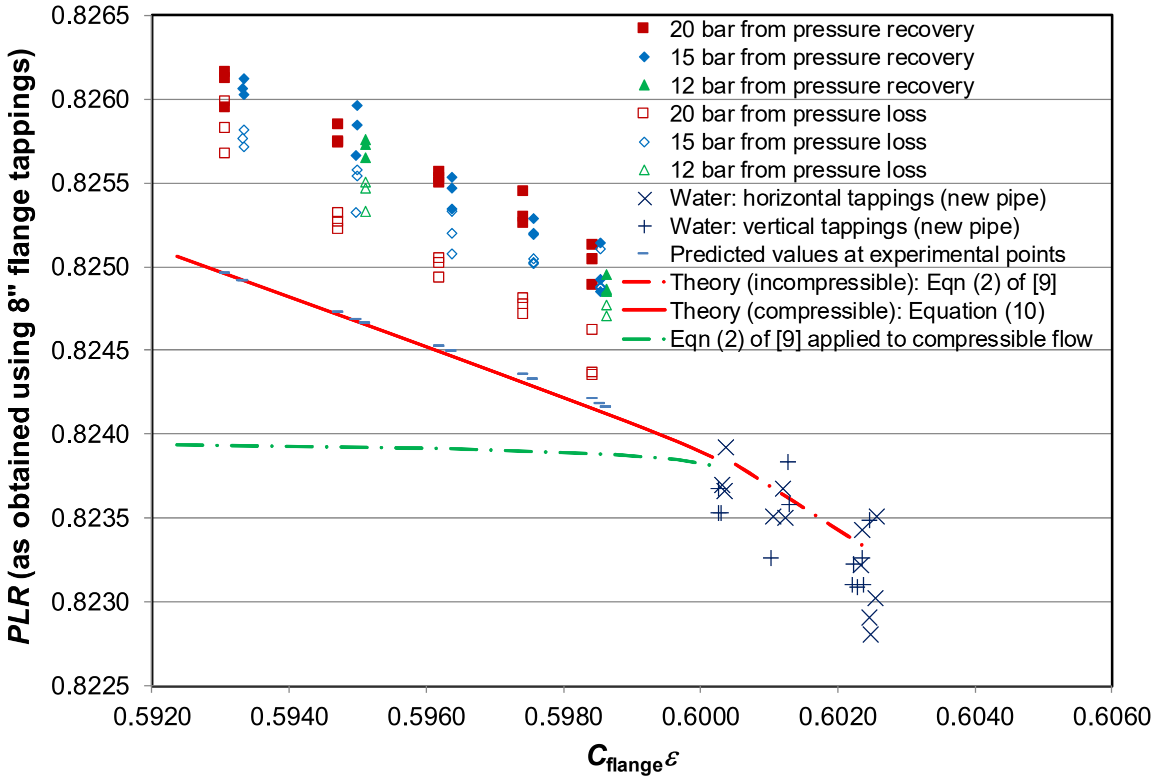

Figure 4 The measured (apparent) pressure loss ratio for the data collected in CO_2

Equation (10), the correlation for *PLR* in dry gas derived in Section 3.2, deviates from the set of data that has been obtained by only 0.0008, but further experimental work with different diameter ratios, different pipe diameters and different gases is required to prove the correlation.

4 CONCLUSIONS

A correlation for pressure loss ratio in dry gas based on theory has been obtained; it deviates from the experimental data that have been obtained in CO_2 by only 0.0008, but further work with different diameter ratios, different pipe diameters and different gaseous phase compositions is required to prove the correlation.

No difficulties in measuring CO_2 with orifice plates were found.

ACKNOWLEDGMENTS

This paper is published by permission of the Managing Director, TUV SUD NEL.

The authors are grateful for funding from the Innovation Funding Initiative (IFI) provided by National Grid.

REFERENCES

1 LEMMON, E. W., HUBER, M. L., McLINDEN, M. O. NIST Standard Reference Database 23: Reference Fluid Thermodynamic and Transport Properties-REFPROP, Version 9.0. National Institute of Standards and Technology, Standard Reference Data Program, Gaithersburg, 2010.

2 PPDS for Windows : NEL, East Kilbride, UK; www.tuvnel.com.

3 STEVEN, R. Diagnostic methodologies for generic differential pressure flow meters. In Proc. 26th Int. North Sea Flow Meas. Workshop, St Andrews. East Kilbride, Glasgow: TUV NEL, October 2008.

4 STEVEN, R. Significantly improved capabilities of DP meter diagnostic methodologies. In Proc. 27th Int. North Sea Flow Meas. Workshop, Norway, October 2009.

5 SKELTON, M., AYRE, J., BARRON, S., and STEVEN, R. Developments in the self-diagnostic capabilities of orifice plate meters. In Proc. 28th Int. North Sea Flow Meas. Workshop, St Andrews. East Kilbride, Glasgow: TUV NEL, October 2010.

6 RABONE, J., BRYCE, A., MORRISON, M., VIJAY, D., GLOVER, B., and STEVEN, R. DP meter diagnostic systems – operator experience. In Proc. 30th Int. North Sea Flow Meas. Workshop, St Andrews. East Kilbride, Glasgow: TUV NEL, October 2012.

7 RABONE, J., PEEBLES, R., KIDD, G., SAFONOV, A., and KINNEY, J. Advanced DP meter diagnostics – Developing dynamic pressure field monitoring (and other developments). In Proc. 32nd Int. North Sea Flow Meas. Workshop, St Andrews. East Kilbride, Glasgow: TUV NEL, October 2014.

8 READER-HARRIS, M. J., LEE, W. K., BARNETT, J., and MISTRY, K. Diagnostics and orifice plates: theoretical and computational work. In Proc. FLOMEKO 17, Sydney, Australia, September 2016.

9 READER-HARRIS, M. J., ADDISON, D., BARNETT, J., and MISTRY, K. Diagnostics and orifice plates: experimental work. In Proc. 34th Int. North Sea Flow Meas. Workshop, St Andrews. East Kilbride, Glasgow: TUV NEL, October 2016.

10 URNER, G. Pressure loss of orifice plates according to ISO 5167-1. *Flow Measurement and Instrumentation,* **8**(**1**): 39-41, 1997.

11 READER-HARRIS, M. J. *Orifice plates and Venturi tubes*. Springer, 2015.

APPENDIX A

NOTES ON PROPERTIES CALCULATIONS

1) REFPROP

REFPROP [1] is the properties of fluids software package available from the United States National Institute of Standards and Technology (NIST). For the calculation of properties of CO_2, CO_2 mixtures and Hydrocarbon mixtures, REFPROP uses the Helmholtz-energy-based equations of state to calculate the properties of the fluids from an input of pressure, temperature and composition. The default for REFPROP is to use the NIST-defined equation coefficients; however, the GERG 2008 industry standard can be selected as an alternative. This uses slightly truncated coefficients. For CO_2 and CO_2 mixtures the differences are insignificant. As the selection of the GERG 2008 implementation is not easy to enable via the Excel interface, the default setting was used for this work.

2) JOULE–THOMSON COEFFICIENT

As gas passes through a restriction it drops in pressure and hence is subjected to Joule-Thomson cooling. As the density of the gas is required upstream of an orifice plate, and temperature is normally monitored downstream to avoid flow disturbance on the orifice plate, the temperature measured has to be corrected to the upstream condition. This correction is specified in ISO 5167; however it depends on the Joule-Thomson coefficient of the gas. For natural gas the coefficient is around 0.4 K/bar, for nitrogen it is around 0.2 K/bar, but for pure CO_2 it is around 1.2 K/bar, some 3 to 6 times greater.

This means that for CO_2 applications the temperature correction is significantly greater than in other common applications. Although this correction is specified as a standard procedure for natural gas fiscal and custody transfer applications, it is often considered unnecessary to apply the correction elsewhere. It is recommended that this correction is always applied to CO_2 metering applications.

3) ISENTROPIC EXPONENT

The expansibility factor (or expansion factor) is applied to the equation for flowrate measured through a differential-pressure meter. The equation to calculate expansibility factor is dependent on the isentropic exponent, which is normally designated as κ.

REFPROP provides isentropic exponent as an output. The NEL PPDS, in common with other calculation models, does not. PPDS provides the isentropic compressibility which, when multiplied by the pressure, is the inverse of the isentropic exponent.

Isentropic exponent is commonly believed to be the ratio of specific heats C_p/C_v, usually designated as γ. This definition can be found in some reference texts. Although this is true for an ideal gas it is <u>not</u> true for a real gas. For some gases at certain pressures the absolute difference between κ and γ may be insignificant. For CO_2 it can be significant, with a difference of 0.25.

Care should be taken in evaluating isentropic exponent correctly for CO_2 applications.