19th NORTH SEA FLOW MEASUREMENT WORKSHOP

Temperature Changes Across Orifice Meters

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1 INTRODUCTION

When a real gas flows through an orifice plate, an irrecoverable pressure loss occurs downsteam due to the expansion of the gas, which results in a temperature drop. Knowledge of the density of the gas at upstream conditions is necessary for accurate calculation of flow rate. If density is measured, a density cell is normally installed at a tapping downstream of the orifice-plate meter, as shown in Figure 1 below. Densitometers incorporate their own temperature sensor but if density is calculated from the gas composition, a temperature sensor is installed in a downstream thermowell. The measurement is made some 8D downstream of the orifice plate in order to avoid flow disturbances. Whichever method is used, the measurement needs to be corrected to upstream conditions. While temperature correction is applicable to both methods, the density measurement also requires pressure correction, since the pressure used in the density calculation method is that taken at the upstream pressure tapping.

For some time now, the industry has been raising the question as to whether National and International standards use the correct method for determining the temperature drop. The internationally recognised standards for orifice-plate metering, such as ISO 5167[1], consider the process that produces the temperature drop to be isentropic. This paper describes a theoretical analysis of the process that governs the nature and magnitude of the temperature drop due to the gas expansion, which occurs when gas flows through an orifice plate. The analysis considers both isentropic and isenthalpic processes. Experiments carried out are also described, which support the theory that the expansion process is isenthalpic.

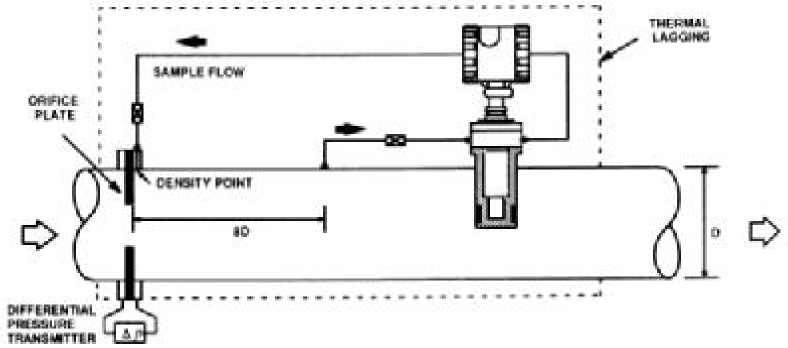
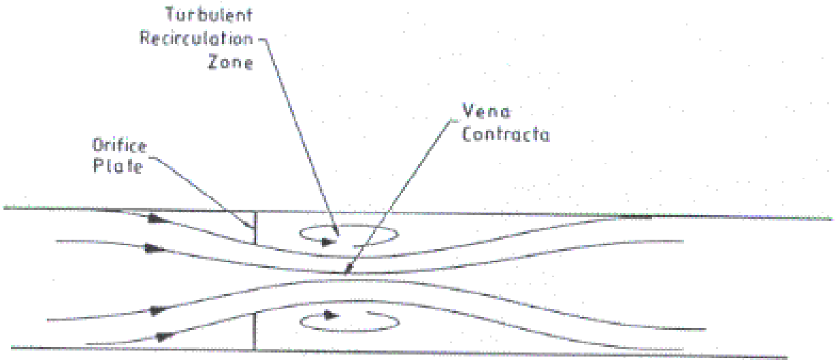


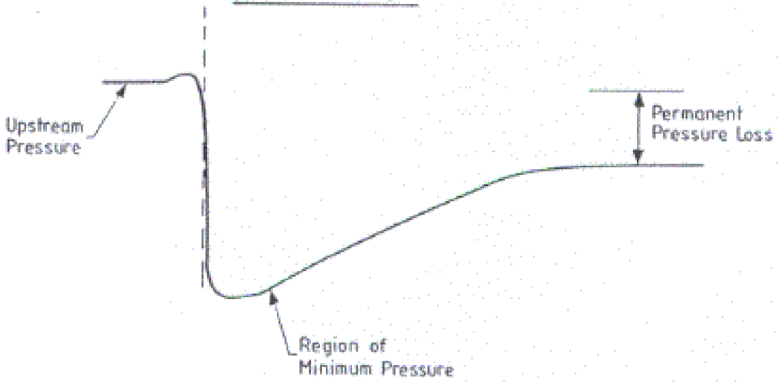
Figure 1. Orifice-plate Metering System with Pressure Recovery Method of Installation of Density Cell

2 THEORY

Figure 2 below shows the flow patterns through an orifice-plate meter.



(a) Flow Pattern



(b) Pressure Variation

Fig. 2 : Flow through an Orifice Plate

According to the draft ISO 5167 the pressure loss, Δw , for orifice plates is approximately related to the differential pressure Δp by:

$$\Delta w = \frac{\sqrt{1-b^{4}\left(1-C^{2}\right)}}{\sqrt{1-b^{4}\left(1-C^{2}\right)}}\,\frac{-Cb^{2}}{+Cb^{2}}\Delta p$$

This pressure loss is the difference between the static pressure measured on the upstream side of the orifice plate, and that measured on the downstream side, where the static pressure recovery is considered to be complete (Figure 2).

Assuming the expansion process is isenthalpic, the corresponding temperature drop between the two points can be evaluated using the Joule Thomson coefficient:

$$m_{\mathrm{JT}} = \left\{\frac{\partial T}{\partial P}\right\}_{H}$$

The isenthalpic expansion is expressed as:

$$\left\{\frac{\partial T}{\partial P}\right\}_{H} = \frac{RT^{2}}{PC_{P}}\left\{\frac{\partial Z}{\partial T}\right\}_{P}$$

In the region of most interest (0 ˚C to 40 ˚C, up to 70 bar), the simple equation for the calculation of compressibility factor, Z, for ‘Mean Bacton Gas’ may be expressed as a simple function of pressure and temperature:

$Z = 1 + bP + cP^{2}$

Where, b = $\left(-264.3+3.5T-0.03T^{2}\right)\times10^{-5}$

c = $\left(120+1.2T+0.093T^{2}\right)\times10^{-8}$

Therefore,

$$\left\{\frac{\partial b}{\partial T}\right\} = \left(3.5-2\times0.03T\right)\times10^{-5}$$

and,

$$\left\{\frac{\partial c}{\partial T}\right\} = \left(1.2+2\times0.093T\right)\times10^{-8}$$

Hence, with the following nominal values for mean Bacton Gas at 70 bar and 10˚C,

T = 283.15˚K

P = 70 bar

R = 8.31434 J/(mol ˚K)

C_P = 0.04732 MJ/(kmol ˚K)

Z = 0,8451

$$\left\{\frac{\partial Z}{\partial T}\right\}_P = P\left\{\frac{\partial b}{\partial T}\right\} + P^2\left\{\frac{\partial c}{\partial T}\right\}$$

= 2.18 $\times$ 10^{-3} /°K

and $\left\{\frac{\partial T}{\partial P}\right\}_H$ = **0.4377 ˚K/bar**

For isentropic expansion however, with Z = 0.8451 ,

$$\left\{\frac{\partial T}{\partial P}\right\}_S = \left\{\frac{\partial T}{\partial P}\right\}_H + \frac{ZRT}{PC_P}$$

= 1.037 ˚K/bar

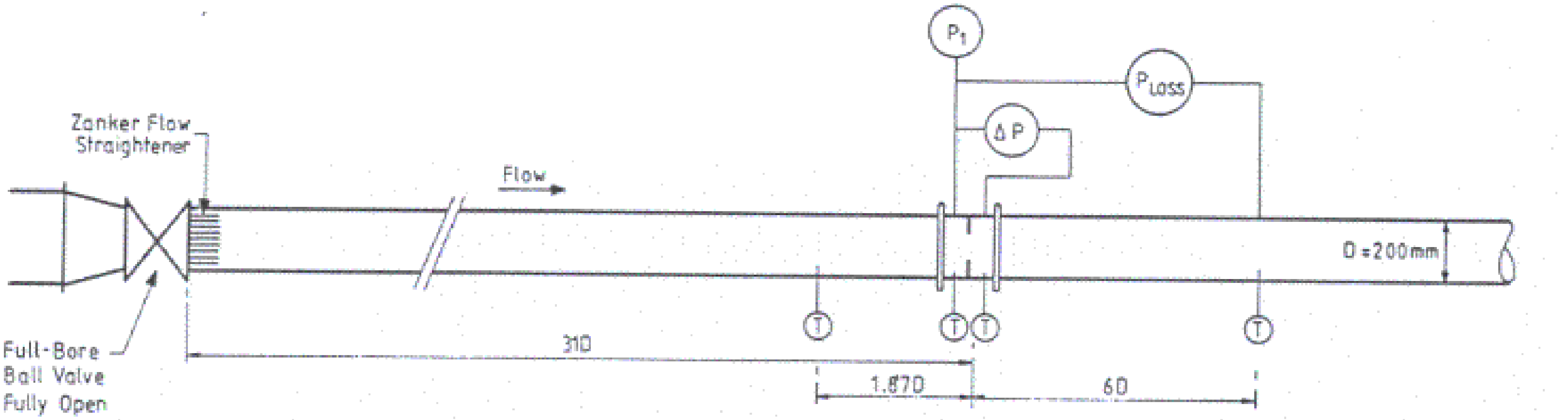
Both the above formulae assume that the process is adiabatic.

3 EXPERIMENTAL ARRANGEMENT

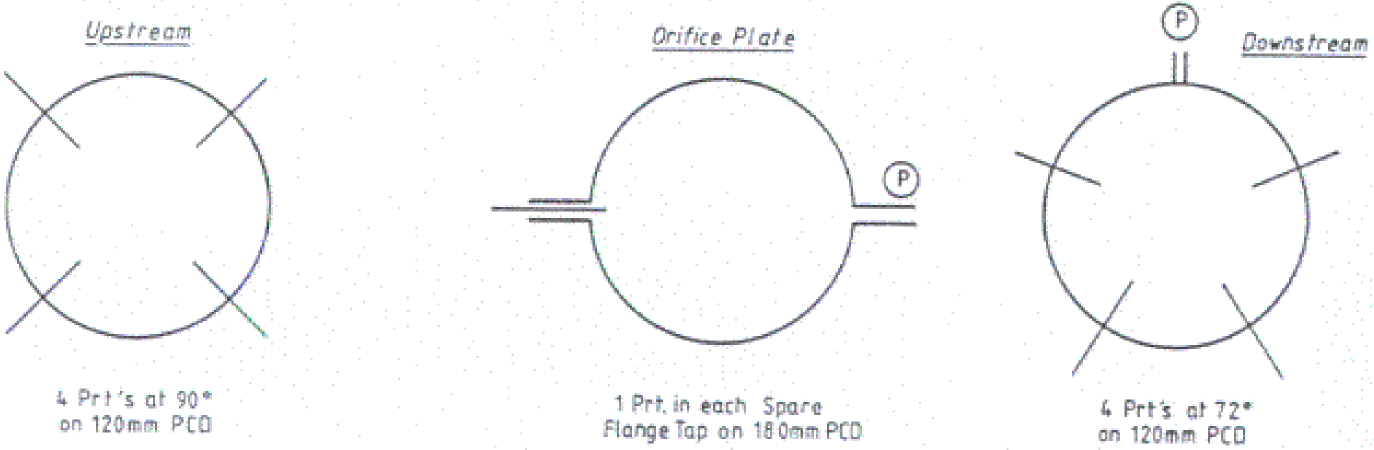
A series of experiments was carried out at our Low Thornley Test Facility in order to determine the correct formula to be used for the temperature drop. A 200 mm pipe was set up as shown in Figure 3 below. A Daniel Junior orifice-plate carrier was installed 30D downstream of a Zanker flow straightener and 20D upstream of a straight pipe. The meter run was insulated for 20D upstream and 10D downstream of the orifice plate in order to provide environmental protection during the experiments.

Four platinum resistance thermometers, 4 mm diameter were installed on the straight pipe directly into the gas stream, 1.87D upstream of the orifice-plate carrier on a PCD of 120 mm. A further four thermometers were installed 6D downstream of the orifice-plate carrier on the same PCD. A pressure tapping was also installed at this location. Orifice-plate temperature was recorded at the plate itself by using the spare set of 13 mm flange tappings and installing two thermometers on a PCD of 180 mm. All of the temperature sensors were calibrated using an oil bath prior to installation.

KDG pressure transmitters were used to measure the upstream static pressure and the differential pressure, as well as the overall pressure loss. Four orifice plates, with β ratios of 0.2, 0.4, 0.6, and 0.75, were manufactured and fully inspected to comply with ISO5167.



(a) General



(b) Details of Temperature Sensors

Fig. 3 : Test Arrangement and Instrumentation

4 TEST METHOD

An in-situ calibration check was carried out on the temperature sensors at the beginning of the experiments using the 0.4 β orifice-plate set-up. The test line was pressurised and allowed to ‘float’ at the upstream Bishop Auckland – Saltwick feeder line pressure (typically about 28 bar and 5˚C) in order to reduce any temperature variations at the orifice plate, which would otherwise occur due to Joule-Thomson cooling effect at the test site’s regulators.

The flow rate through the set-up was increased until the orifice-plate pressure differential (ΔP) was 50 mbar. All ten temperature sensors were sampled twenty times over a period of 10 minutes in order to observe any differences between the temperature readings at very low ΔP. It was expected that at this low pressure differential all of the temperature sensors would read approximately the same. Flow rate was then increased until the differential pressure was 250 mbar and then in steps of 250 mbar up to a maximum of 1.5 bar. Data for pressures, differential pressures and temperatures were recorded at each step. At the end of these tests, the flow rate through the orifice plate was reduced so that the ΔP was 50 mbar for a final test, to ensure that no drift had occurred in the sensors or the data logging circuitry.

The remaining three plates were then tested in turn. During the experiments with the 0.6 β and 0.75 β plates the test method had to be changed. This was due to the operational restrictions on the flow rates available through the site. For these two plates, the flow rate through the system was slowly increased from 50 mbar differential to maximum differential over a period of approximately 16 minutes, logging all of the pressure and temperature sensors every 18 seconds. For each test, gas samples were analysed and values for the gas properties Z, M, Cp and $\left(\frac{\partial Z}{\partial T}\right)$ were calculated, using the Advantica programme GasVLe[2]. Gas composition ranges, together with test conditions, are shown in Table 1 below:

Table 1	β RATIO			
	0.2	0.4	0.6	0.75
Temperature Range (^{o}K)	9.7 - 11.1	2.1 - 4.2	4.4 - 8.3	9.0 - 23.0
Pressure Range (Bar)	30.9 - 31.4	27.5 - 29.8	27.8 - 32.0	32.4 - 37.2

GAS COMPOSITION RANGE

Component	Mol %		
Methane	94.137	-	95.568
Ethane	3.041	-	4.194
Propane	0.146	-	0.38
n-Butane	0.011	-	0.044
i-Butane	0.008	-	0.028
n-Pentane	0.003	-	0.007
i-Pentane	0.001	-	0.006
Hexanes	0.011	-	0.03
Carbon Dioxide	0.415	-	0.446
Nitrogen	0.699	-	0.746
Molecular Weight	16.748	-	17.008

5 RESULTS AND DISCUSSION

The temperature drop between upstream and 6D downstream of the orifice plate is shown in Figures 4 & 5.The temperature drop has been calculated as the difference between the means of the four upstream and the four downstream thermometers. It can be seen from these two graphs that the consistency in the results for the two smaller β ratio plates, 0.2 and 0.4, was very good and the same results were obtained for the individual temperature sensors rather than plotting the average values. For the two larger β ratio plates, 0.6 and 0.75, the results were much more scattered. This was due to the way the tests were conducted which prevented the use of a 10 minute averaging period.

During the commissioning of the system, i.e. when the flow rate was zero, differences of up to 0.08 ˚K between the upstream and downstream sets of thermometers were observed. This was attributed to scatter arising form the calibration of the thermometers. These offsets are shown in Table 2, second row, below:

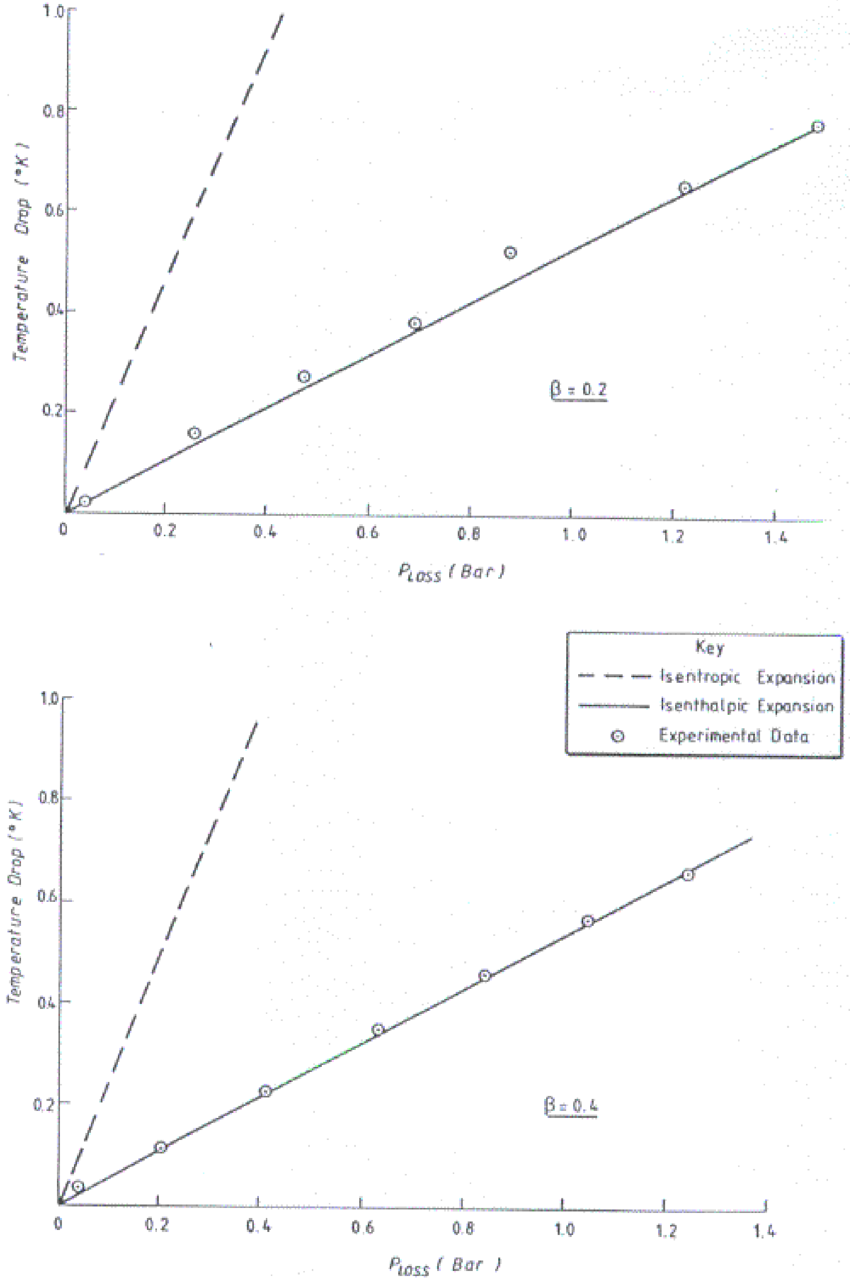
Table 2: OFFSETS OBSERVED AT ZERO FLOW ON DOWNSTREAM THERMOMETERS

(RELATIVE TO UPSTREAM THERMOMETERS)

LOCATION	β RATIO			
	0.2	0.4	0.6	0.75
Downstream Flange Tap	-0.4	0.08	-0.46	0.05
6 Diameters Downstream	-0.07	0	0.03	-0.05

These offsets were then corrected for in Figures 4 and 5 below, assuming that the temperature difference is zero.

It can be seen that the temperature drop for each plate is proportional to the pressure loss and that the agreement between the experimental and the theoretical isenthalpic values is extremely good.



Temperature Drop/Pressure Loss Results

Figure 4

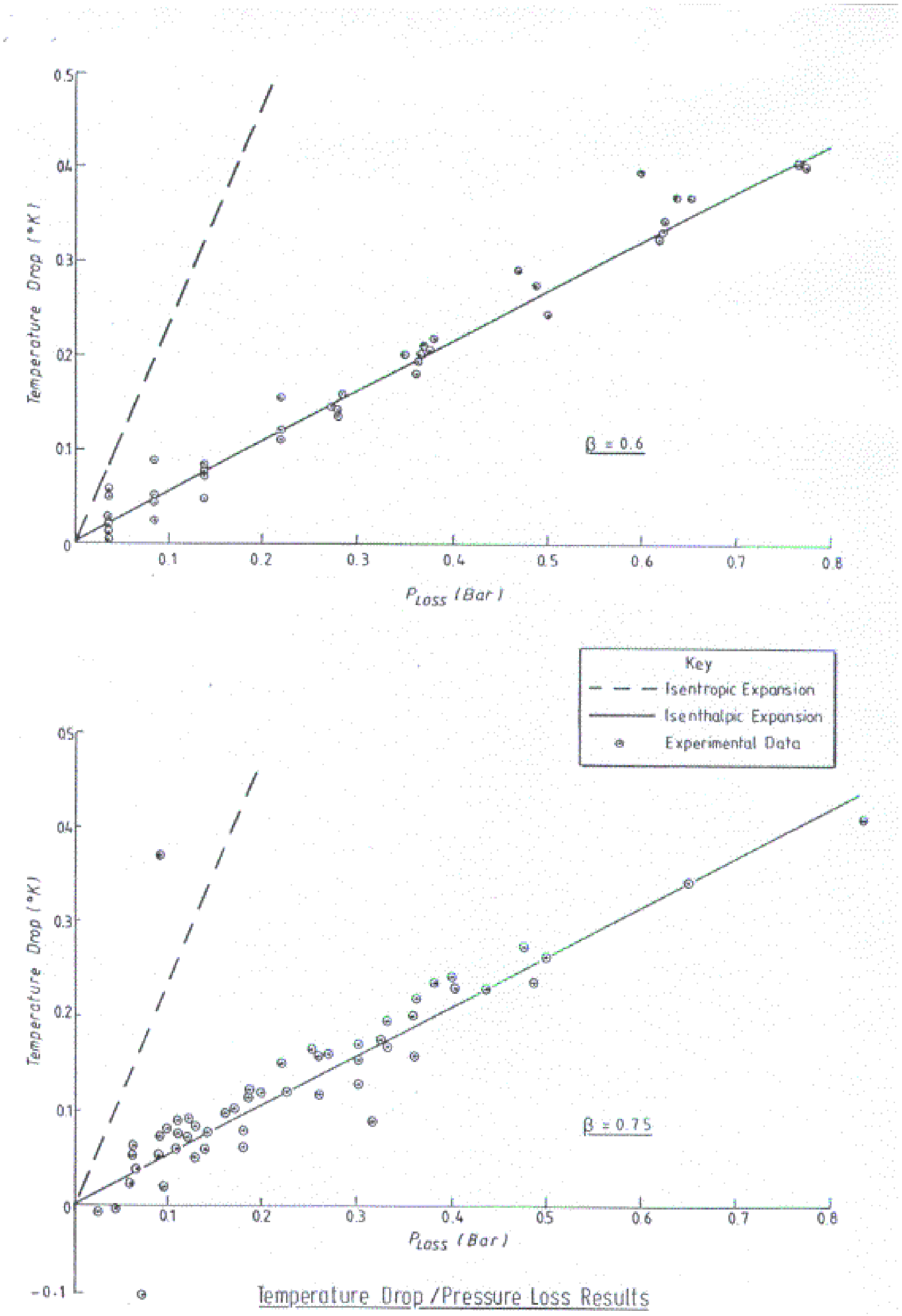


Figure 5

One of the reasons for carrying out the experiments at a low pressure of 28 bar was that at this pressure, assuming Mean Bacton Gas composition and the following values:

T = 278.15 ˚K (5 ˚C)
P = 28.6 bar abs
Cp = 0.0397 MJ/Kmol ˚K
R = 8.31434 J/(mol ˚K)

$$\left(\frac{\partial Z}{\partial T}\right)_P = 0.9326\times10^{-3}\ \text{˚K}^{-1}$$

Therefore,

$$\left(\frac{\partial T}{\partial P}\right)_H = 0.528\ \text{˚K/bar}$$

and with Z = 0.9298

$$\left(\frac{\partial T}{\partial P}\right)_S = 2.422\ \text{˚K/bar}$$

The large difference between the predictions of the two formulae at this pressure makes the interpretation of the results very straightforward.

Stagnation Temperature Rise

A secondary effect, which could cause errors in the measured temperatures, is the stagnation temperature rise which occurs when flowing gas is brought to rest in front of a probe. This is given by:

$$\Delta T_{STAG} = \frac{V^2}{2\left(\frac{C_P}{M}\right)}$$

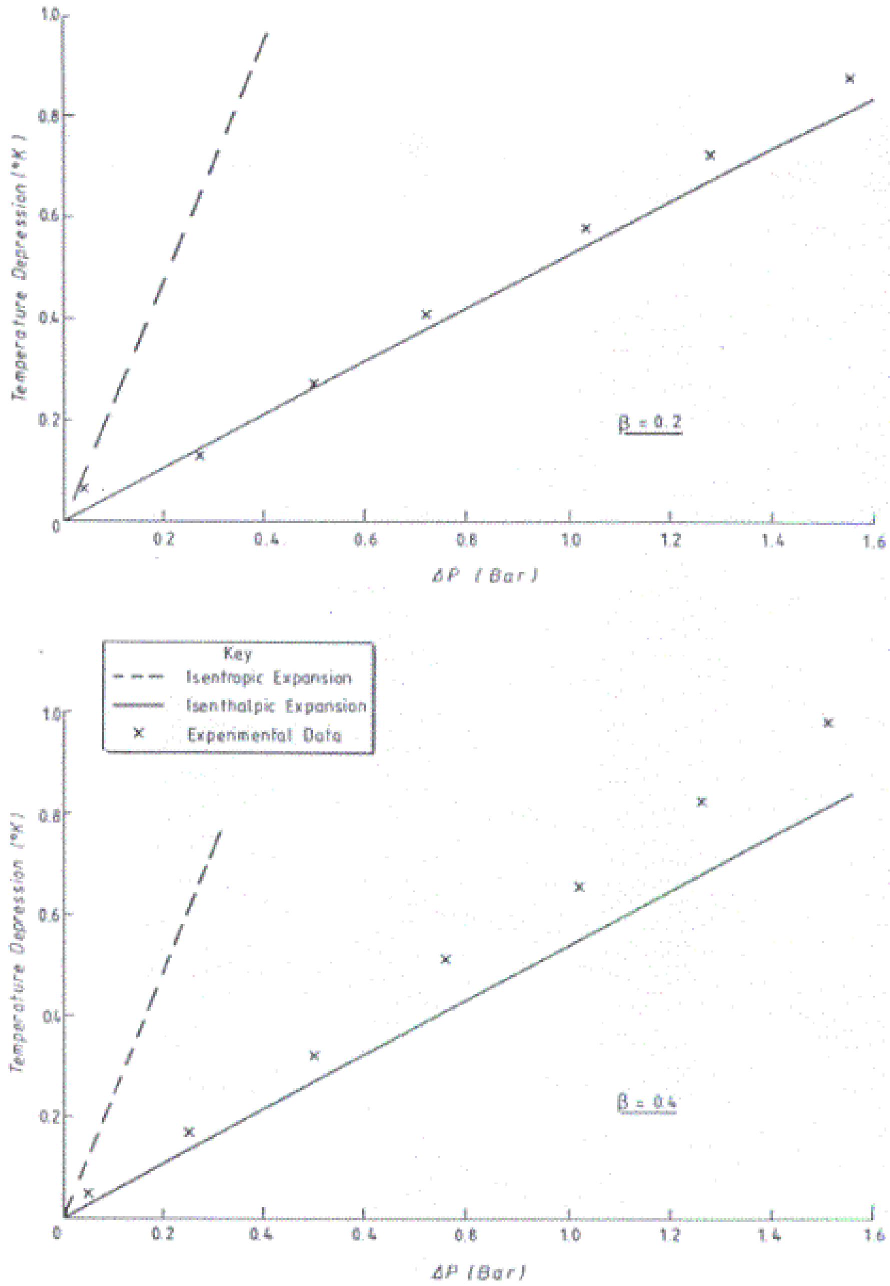
With the exception of the downstream flange probe, it was expected that, where the gas velocity is very low, all of the probes would be affected to some extend. Table 3 below shows that the maximum stagnation temperature rise for the upstream thermometers was 0.38 ˚K with Cp = 47430 J/(kmol ˚K) and M = 17 (approx.). With the exception of the downstream flange tap probe, all probes would have been affected by virtually the same amount.

Table 2: STAGNATION TEMPERAURE RISE

β	V (m/s)	ΔT_{STAG}
0.2	2.8	0.002
0.4	11.2	0.022
0.6	23.8	0.102
0.75	46.3	0.384

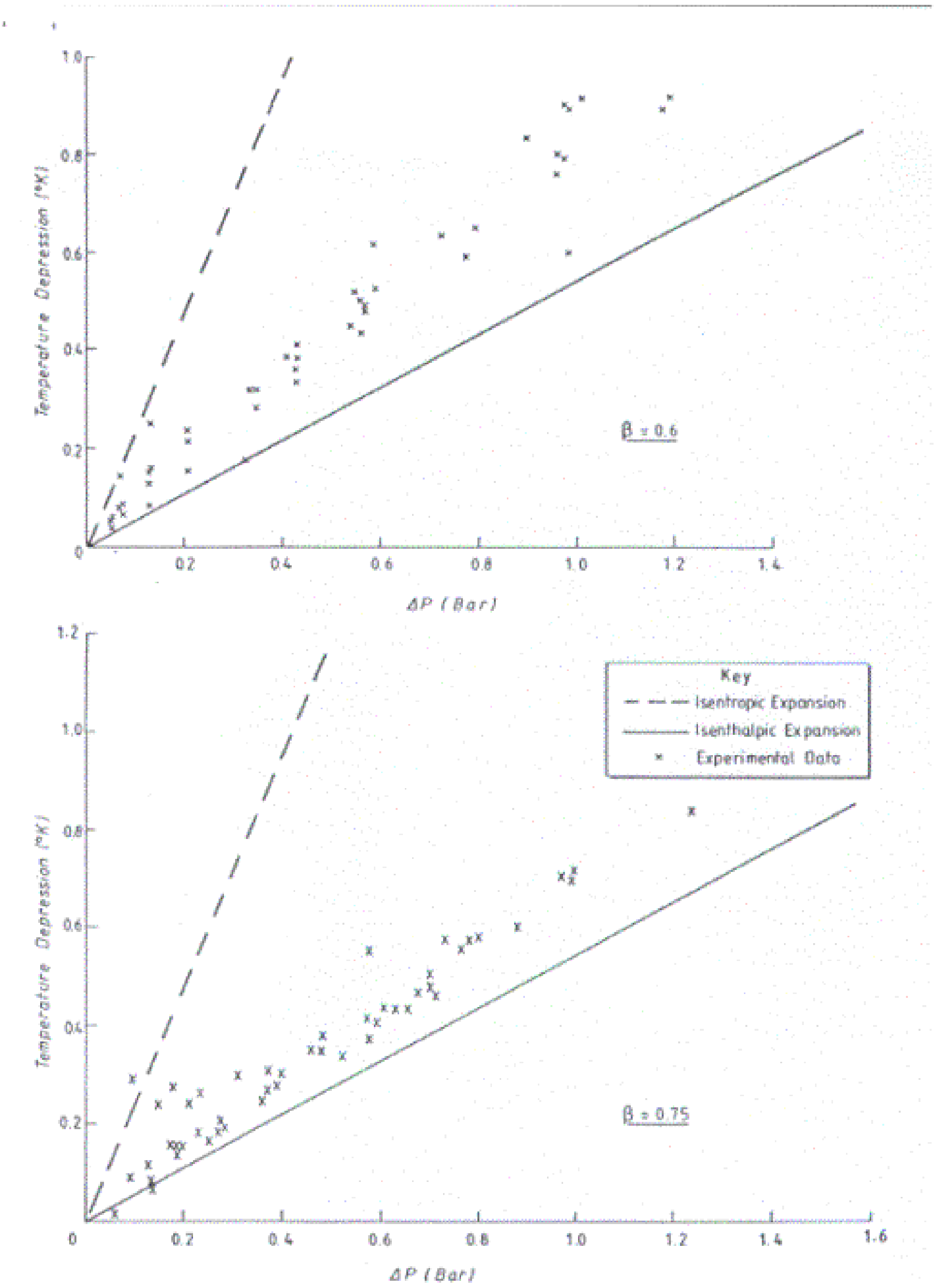
There will be a difference in upstream and downstream stagnation rises due to the change in density across the orifice plate. Since the density decreases by approximately 4% across the plate, the downstream stagnation temperature rise will be greater than the upstream one by approximately 8%, i.e. 0.03 ˚K for the 0.75 β plate. This is a very small rise in the stagnation temperature and therefore this effect can be neglected.

Whilst not essential to the experiment, the thermometers installed in the spare flange taps have shown interesting results. With the exception of the 0.75 β plate tests, the upstream sensor effectively remained at the temperature of the other four upstream sensors. The downstream sensor showed an offset of up to 0.46 ˚K at zero flow (Table 2). It was suspected that this might have been due to the close proximity of the large thermal mass of the orifice-plate carrier. During the tests with the 0.75 β plate, the two flange-tap sensors showed erratic behaviour relative to the upstream and downstream sets. The difference between the two flange tap sensors, however, was consistent and varied linearly with the flow. The slopes of the temperature drop/differential pressure graphs for the downstream sensor varied with β ratio and ranged from 0.5 ˚K/bar for the 0.2 β plate to 0.8 ˚K/bar for the 0.6 β plate, Figures 6 & 7 shown below. This variation can only partly be attributed to stagnation temperature differences between the downstream flange tap and the downstream set of thermometers (the downstream flange tap probe will read cold due to this effect relative to all the other probes). The variation in slope may have resulted from the combination of low gas velocity in this re-circulation zone together with the thermal mass of the orifice-plate carrier. Further work is needed to confirm the gas temperature in this region.



Temperature Depression at Downstream Flange Tap

Figure 6



Temperature Depression at Downstream Flange Top

Figure 7

6 CONCLUSIONS

The temperature change across orifice plates from upstream to a plane 6D downstream of the plate were found to be approximately 0.54 ˚C/bar at pressures and temperatures in the ranges 27 – 32 bar and 2 – 12 ˚C.

All four β ratio orifice plates tested (0.2, 0.4, 0.6 and 0.75) showed the same behaviour.

The experimental results agreed extremely closely with the assumption that the expansion across an orifice plate is isenthalpic.

7 REFERENCES

1 ISO 5167-1 1991. Measurement of fluid flow in close conduits. Part 1. Pressure differential devices.

2 Laughton, A. GasVLe (Version 4.1). Advantica Technologies Ltd.

8 ACKNOWLEDGEMENTS

The authors wish to acknowledge both the practical and theoretical studies carried out by Dr Roger Norman which form the basis of this paper. (Dr Roger Norman is no longer employed by Advantica Technologies Ltd).