Estimation of the Measurement Error of Eccentrically Installed Orifice Plates

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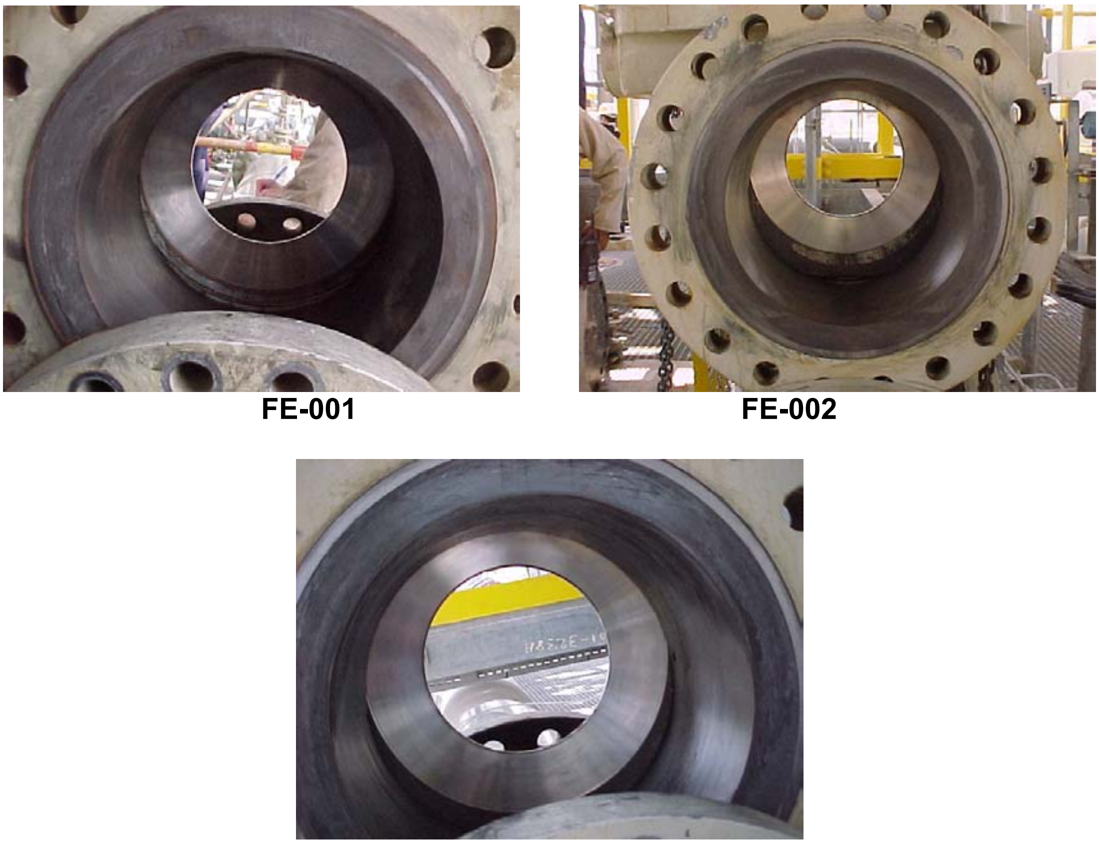
Introduction

An inspection of the fiscal metering station on a large Middle Eastern gas field revealed that the orifice plates in all three 16-inch metering runs had been incorrectly inserted in their carriers and O-rings sealing the plates had been damaged. As a consequence, all of the orifice plates were eccentric within their carriers. This paper describes the subsequent investigation into this problem and the estimation of the resultant flow-measurement error.

Initial Inspection and Testing Work

Figure 1 shows the three flow meters. The displacement of three plates (FE-001, FE-002 and FE-003) was measured as being 36 mm, 56mm and 39 mm and they were significantly outside eccentricity limits set in ISO 5167 [1]. In all three cases the O-rings were incorrectly sized and had been sheared when the plates had been inserted. The FE-002 plate had a clear 11 mm gap under the plate.



FE-001 **FE-002**

FE-003

Figure 1. The orifice plates on initial inspection

After further investigation it was established that the number of turns of the elevator screw required to correctly seat the orifice plate during installation had been incorrectly marked on the outside of the orifice-plate carrier.

To assess leakage rates through the damaged seals, the metering tubes were removed, the upstream flanges blanked off and the orifice plate holes were sealed closed. A pressure was fed into the tapping on the upstream side of the blanked orifice plate with a compressed air supply and the leakage flow rate was measured. For plates FE-001 and FE-003 a leakage flow rate of 10.5 Nm^3/hour was measured for a 1 bar pressure difference across the plate. For plate FE-002 the leakage rate exceeded the range of the flowmeter used in the tests.

Review of Published Information on Eccentric and Leaking Orifice Plates

In general very little information has been published on leaking or eccentric orifice plates. Some work has been performed in the development of fully eccentric orifice plates in which the lower edge of the orifice coincides with the pipe bore. This type of orifice plate is used in slurry flows, as it allows particulates travelling along the pipe bottom to pass through the plate. This type of plate differs from the plates in this problem in that it is more eccentric and the tappings are positioned at the top of the pipe with the orifice at the bottom rather than on the side of the pipe.

Fully eccentric orifice plates are described in ISO/TR 15377 [2]. This document gives the discharge coefficient of an eccentric orifice plate with a diameter ratio of 0.6 to be 0.629. Comparing this with the discharge coefficient values given for concentric plates [1] suggests that a fully eccentric plate would be in error by -4.2% if it was mistakenly assumed to be concentric.

Yadav et al [3] provide detailed measurements of discharge coefficient of a 40mm eccentric orifice plate, in water flow, over a range of flow rates. The data presented agrees well with ISO/TR 15377 and shows that the discharge coefficient is independent of flow rate above a Reynolds number of 70000. In our case this suggests that the metering error caused by eccentricity is likely to be independent of flow rate for the flow rates at which the station operates.

In the mid-eighties Norman et al [4, 5] of British Gas performed experiments to assess the effect of eccentricity on 150mm orifice plates in atmospheric pressure air flows. This data is also presented in ISO TR 12767:1998 [6]. These tests provide very detailed information on the effects of eccentricity with a number of alternative tapping arrangements up to an eccentricity value at slightly lower eccentricities than in our case.

Similar work was performed by Husain and Teyssandier [6] on a 50 mm orifice plate in water flow. The data generated in this work agreed well with the work of Norman et al and it was concluded that eccentricity effects are not a function of line size, Reynolds number (i.e. flow rate) or fluid density.

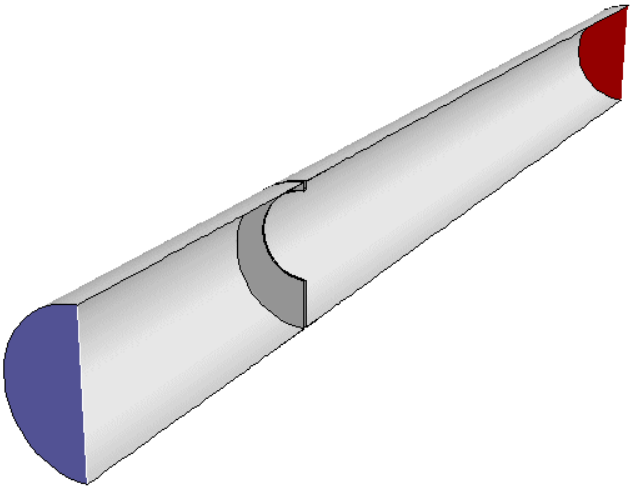
Miller & Kneisel [7] ran a series of tests on 100 mm orifice plates with different diameter ratios. The results of these tests agree well with those of Norman et el and Husain and Teyssandier, but they are for a larger range of eccentricities.

No detailed information has been found on the effect of leakage past orifice plates. The only document found on this subject was on the Daniel website [8] which suggested that errors exceeding 8% in magnitude were possible in our case.

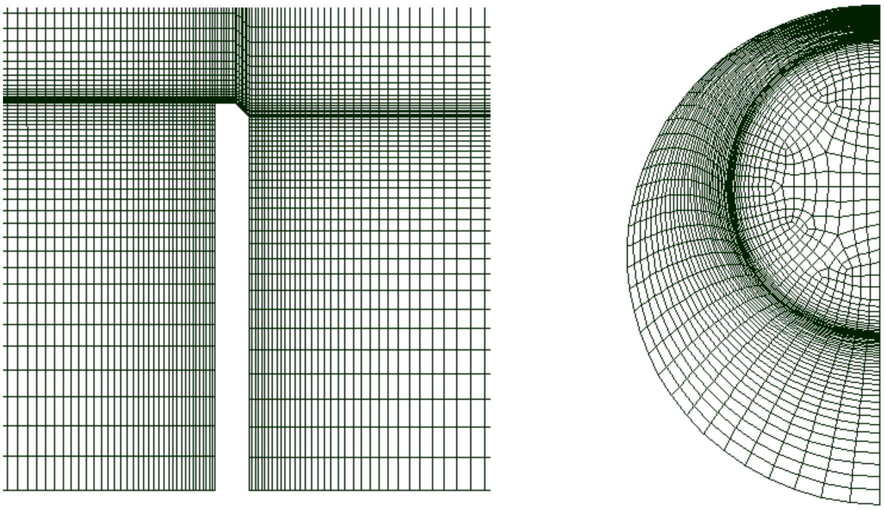
However, no detailed information is given on the tests performed or the size of meter tested; therefore it is unclear as to how representative these tests are of our problem.

Computational Fluid Dynamics Investigation

A CFD-based study was subsequently initiated to investigate the problem further. A range of simulations were run to determine how plate eccentricity and leakage affected the flow measurement error. Figure 2 shows a typical computational domain and the computational mesh used for a simulation without leakage.



a) Computational domain



b) Mesh detail **c) Mesh detail**

Figure 2. The computational domain and mesh

Figure 3 shows how an eccentric orifice plate causes the jet issuing from the orifice plate to be pushed towards the top of the pipe. This results in a distorted pressure distribution on the pipe walls downstream of the orifice plate (see Figure 4). Figure 4 shows that the effect of eccentricity will vary depending on the radial and axial location of the tappings and the number of tappings used. In particular, Figure 4 suggests that the results of tests performed with small orifice plates with flange tappings may not always be representative of larger, flange-tapped flowmeters.

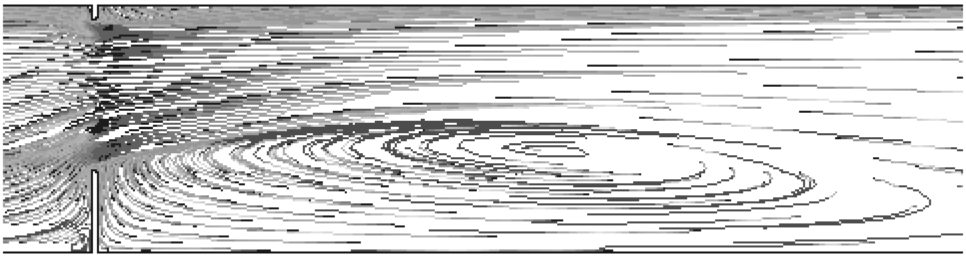


Figure 3. Streamlines showing the predicted flow pattern in eccentric plate

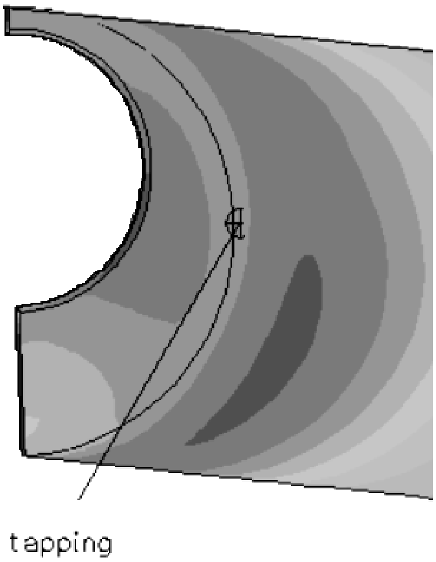


Figure 4. Predicted pressure contours downstream of an eccentric orifice plate
(high pressure = dark grey, low pressure = light grey)

Figure 5 compares the CFD predictions for the gas metering station with data from air flow and water flow tests [5 & 7]. In Figure 5 eccentricity is defined as:

$$Eccentricity = \frac{x}{D}$$

where

x is the displacement of the centre of the orifice hole from the pipe axis (m)
D is the pipe diameter (m)

Eccentricity values for plates FE-001, FE-002 and FE-003 were 0.088, 0.14 and 0.095 respectively. A fully concentric plate has an eccentricity of zero and a fully eccentric plate, with the orifice edge just at the pipe wall, has an eccentricity value of 0.197.

In general, a very good agreement was achieved between the CFD simulations and published test data, although some discrepancies were apparent at higher eccentricities. This is partly caused by the scaling effect previously mentioned and partly by assumptions and simplifications inherent in the CFD simulation method.

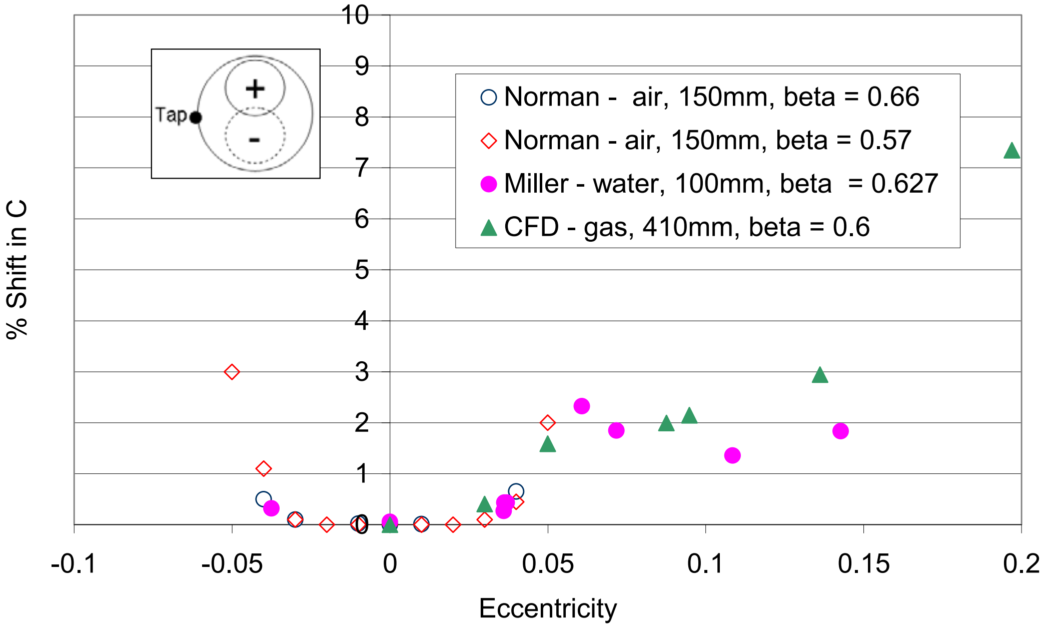


Figure 5. **Predicted and measured effect of orifice plate eccentricity**

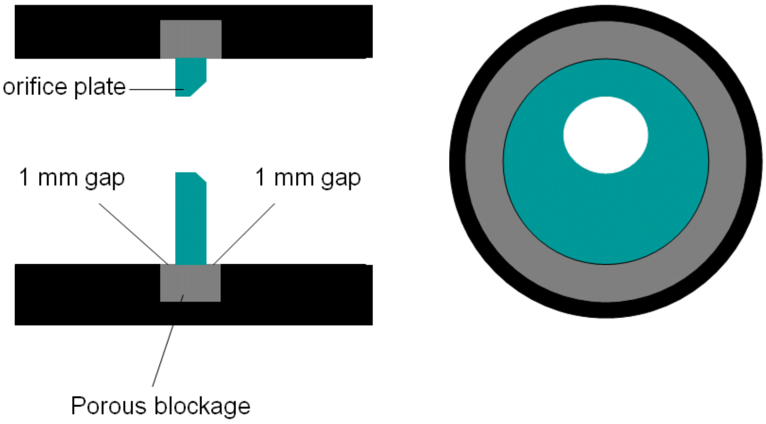
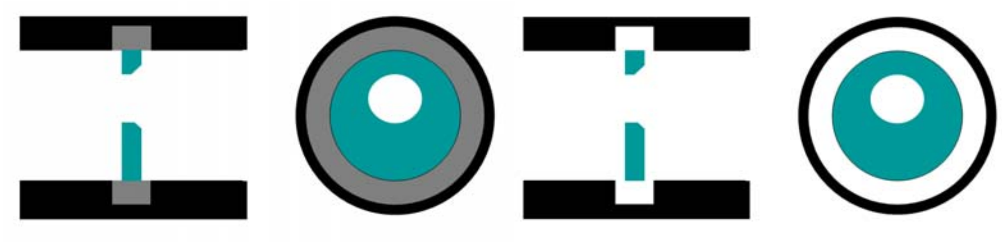
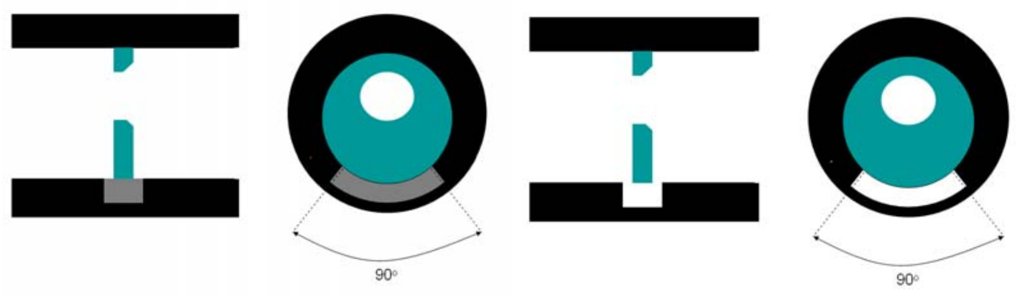


Figure 6. **Geometrical arrangement of porous blockage**



a) Leak 1 (even leakage) **b) Leak 2 (high leakage)**



c) Leak 3 (leakage at pipe bottom) **d) Leak 4 (high leakage at pipe bottom)**

e) Leak 5 (11mm gap under plate)

Figure 7. Different leakage scenarios modelled

A series of simulations were also run to assess the effect of leakage on the eccentric plates. To facilitate this, an annular volume was added to the simulation geometry which was intended to be a simplified representation of the slot in the carrier body (as shown in Figures 6). This slot connected the upstream and downstream sides of the orifice plate and allowed a peripheral leakage flow to pass under the plate. Depending on the leakage scenario being modelled, the slot was filled with porous material whose flow resistance could be adjusted to control the leakage rate through the slot.

Figure 7 shows the five leakage scenarios considered. In the Leak 1 scenario (Figure 7a) the resistance to flow in the slot was set to a constant value around the whole pipe circumference. Simulations were run of the orifice plate in the leakage tests and the porosity of the slot blockage was adjusted until an appropriate value had been found which matched the leakage test data.

In the Leak 2 scenario (Figure 7b) no porous blockage was present. This simulation produced an even leakage around the plate periphery which should be significantly higher than occurred in reality.

In the Leak 3 scenario leakage was only permitted at the bottom of the pipe (Figure 7c). As in the Leak 1 models, the blockage porosity was adjusted to match leakage tests. It is believed that the Leak 3 simulations were most representative of the actual leakage behaviour in plates FE-001 and FE-003.

The Leak 4 scenario was similar to the Leak 3 scenario, but with no porous blockage in the slot (Figure 7d).

In the Leak 5 scenario there was no leakage at the periphery of the orifice plate, but an 11mm gap was included under the plate (Figure 7e).

Figure 8 shows the predicted error caused by the different leakage scenarios. It was found that Leaks 1 and 3 cause negligible additional error, Leak 4 causes an additional error of about -0.6%, Leak 2 causes an additional error of about -0.9% and Leak 5 causes an additional error of -4%. The results also show that the flow measurement error caused by leakage depends only on the total leakage flow rate and is independent of the distribution of leakage around the periphery of the plate.

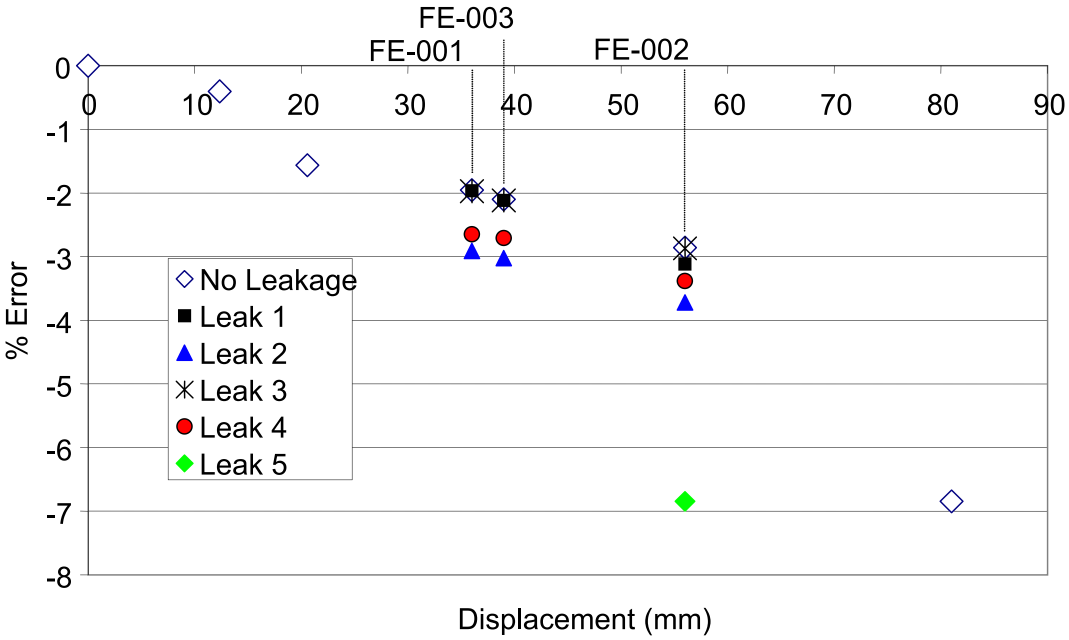


Figure 8. Predicted flow measurement errors

Estimation of Total Flow measurement Error

Over the first two year period of mis-measurement it was believed that the seals in the orifice plates were compromised but that the orifice plates were concentric. Over the second mis-measurement period of one year the plates were eccentric and the seals were definitely leaking.

Based on this information and the results of the CFD study, correction factors were developed representing high and low seal leakage scenarios, as shown in Table 1. These correction factors were used in the following equation to correct historic flow measurements:

$$Corrected\ Flow\ Measurement = CF \times Measured\ Flow\ Rate$$

	Leakage Scenario	**Mis-measurement Period 1**	**Mis-measurement Period 2**
FE-001	Low	1	1.019
FE-002	Low	1	1.068
FE-003	Low	1	1.021
FE-001	High	1.009	1.028
FE-002	High	1.009	1.068
FE-003	High	1.009	1.030

Table 1 Correction Factors CF

Figures 9 and 10 show the corrected gas flow data over the May 1999 to May 2002 period for both scenarios. The low leakage scenario predicts that the measured volume of gas passing through the metering system was 12586 mmscf less than the actual volume of gas. The high leakage scenario predicts a discrepancy of 18343 mmscf. A compromise value of 15471 mmscf was agreed between the gas vendor and their customers for compensation purposes. This volume of gas had a monetary value in excess of $10,000,000 US.

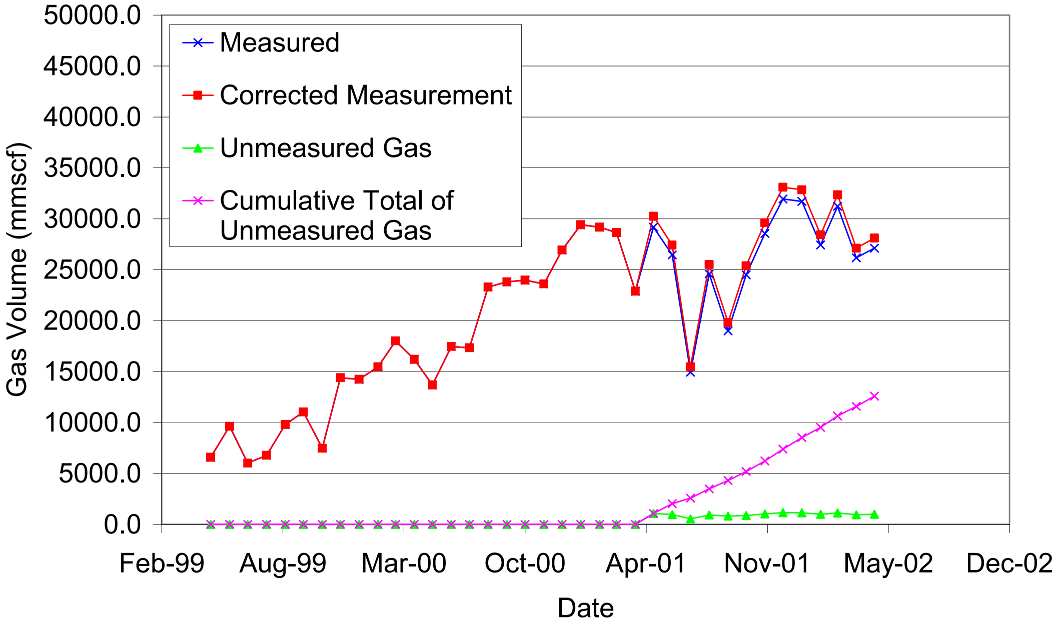


Figure 9. Corrected gas flow measurements (low leakage scenario)

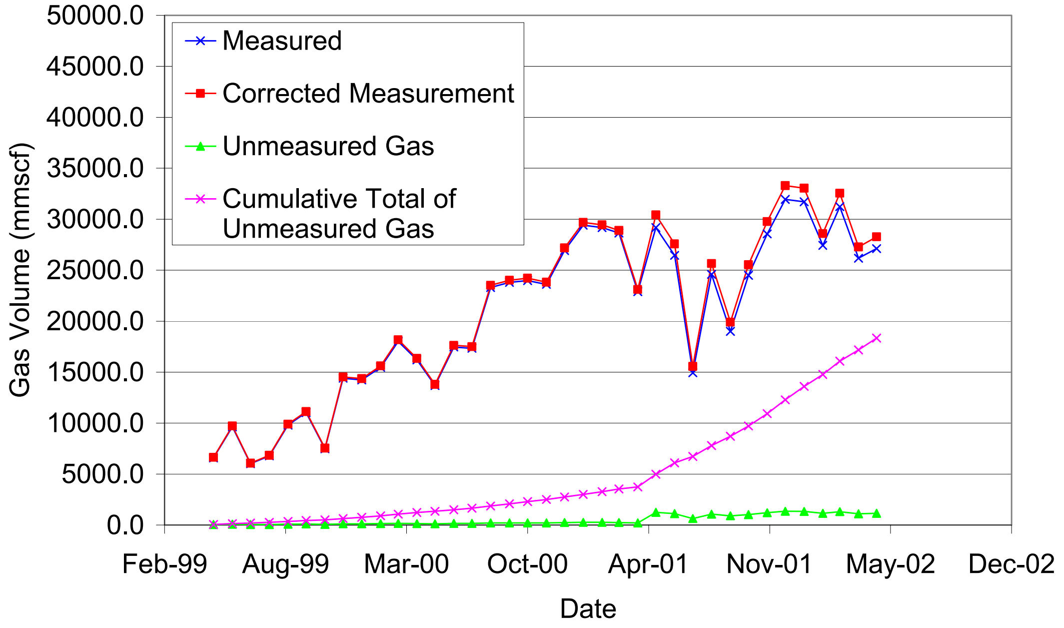


Figure 10. **Corrected gas flow measurements (high leakage scenario)**

Conclusions

CFD simulation methods and published test measurements have been used to estimate the error of a metering system over a period when its orifice plates were eccentric and when leaking O-rings allowed some gas to bypass the meter.

It was found that plate eccentricity effects would result in errors of between -2% and -3% for individual meters. Validation against test data suggests that these estimates of error should be within 1% of the actual error, but it is unclear whether the simulations over-estimate or under-estimate the error.

Simulations were also run to assess how leakage at the periphery affects the metering error. Various alternative leakage scenarios were modelled and it was found that the leakage rate has an effect on the error, but that the leakage distribution does not.

Correction factors, based on the CFD results, were then used to predict the system's mis-measurement over a three-year period.

8 REFERENCES

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