Index

Paper 2.2

An Assessment of the Impact of Contamination on Orifice Plate Metering Accuracy

Michael Pritchard and David Marshall
Advantica Ltd

John Wilson
National Grid Transco

North Sea Flow Measurement Workshop
26–29 October 2004

AN ASSESSMENT OF THE IMPACT OF CONTAMINATION ON ORIFICE PLATE METERING ACCURACY

Dr Michael Pritchard, Advantica
Mr David Marshall, Advantica
Mr John Wilson, National Grid Transco

1 INTRODUCTION

The design, installation, operation and maintenance of orifice plate metering systems are covered by the ISO 5167-1:2003 standard [1]. Evidence from various studies [2, 3, 4, 5] has shown that contamination of the orifice plate results in the metering system operating outside this standard and tends to result in an under registration of gas flow. This under registration is a metering error. Quantification of any error should be made by reference to the BS ISO TR 12767:1998 standard [6]. Although there is a strong indication from the BS ISO 12767:1998 standard and from other reported studies that non gaseous orifice plate contamination results in a meter under registration it is not possible to use these studies directly to quantify the measurement uncertainty due to orifice contamination, as they do not collectively cover the typical operating conditions of the National Transmission System (NTS).

The experimental work, that is the basis for the ISO 12767 standard, was undertaken, primarily by British Gas (Transco's predecessor) in the 1970s at atmospheric pressure with air as the gas medium. This work revealed metering errors ranging from zero to 24% for various degrees of contamination, caused by pipeline sludge, oil, grease, liquids, etc. These test conditions do not reflect current operational practice, therefore the need to assess the validity of the estimated errors when used under actual operating conditions. An initial series of experiments was therefore undertaken by National Grid Transco (NGT) and Advantica to repeat some of the work presented in ISO 12767, but at more representative NTS operating conditions [7]. This work confirmed that orifice plate contamination could lead to meter measurement uncertainty. However, it also identified the need to evaluate more realistic contamination patterns than are covered by ISO 12767.

Therefore to further enhance the understanding of the effect of more realistic orifice plate contamination on flow rate measurement uncertainty, NGT, in conjunction with Advantica Ltd., have conducted a further experimental study looking at different contamination patterns again using more representative NTS operating conditions.

The main finding from this study indicates that any contamination on the surface of an orifice plate will increase the meter measurement uncertainty. This study found that this uncertainty resulted in an under registration of gas flow. These findings are consistent with the work previously undertaken by British Gas that is the basis of the current industry standard ISO12767 and add to the understanding in this field.

This paper presents the findings from this latest study.

2 ORIFICE METERING SYSTEMS

The technology of an orifice-plate meter is well established, with design and installation requirements described in BS EN ISO 5167 and AGA3 [8]. The meter consists of an orifice-plate housed in a carrier, with sufficient lengths of upstream and downstream straight pipe to ensure a fully developed uniform flow at the orifice-plate. The gas flow through the meter causes a pressure difference across the orifice-plate, which is measured by differential pressure transmitters. The greater the flow rate the higher the generated differential pressure.

Normally, good orifice-plate metering systems utilise three differential pressure transmitters:

low	typically	0 - 50 mbar
high	typically	0 - 500 mbar
standby	typically	0 - 500 mbar

The low and high range transmitters are used in a switching arrangement, such that the low-range reading is used in the flow calculation, if the differential pressure is within approximately its maximum calibrated span, and the high-range value is used otherwise. Utilising low and high transmitters improves the rangeability of the orifice-plate.

There are three types of differential pressure tapping arrangements for orifice-plate meters: flange, corner, and D and D/2 pressure tappings. Most commonly, orifice-plates are fitted with a flange-tapping arrangement.

To minimise its effect on the flow profile, the temperature transducer is mounted downstream of the orifice-plate and the temperature measured is corrected to an upstream value in the flow computer. The static pressure is taken from the upstream leg of the orifice-plate differential pressure tappings. In order to meter very large flows, two or more streams are used in a parallel arrangement.

The discharge coefficient of a pressure differential device, C, is given by following equation:

$$\mathrm{C} = \frac{4q_m}{\varepsilon_1 \pi d^2}\frac{\sqrt{1-\beta^4}}{\sqrt{2\Delta p \rho_1}}$$

The sharp edge of an orifice plate ensures separation of flow and consequently contraction of the fluid stream to the vena contracta, located downstream of the plate. The contraction coefficient C_c is defined as the flow area divided by the geometric area and is typically about 0.6. If for example an orifice plate and a rounded edge this would reduce the separation and increase $C_{c,}$ leading to reduced velocities in the vena contracta and a reduction in the observed differential pressure. From the equation above the discharge coefficient would therefore increase. If no correction is made for this change in the discharge coefficient then the meter will under read. *Thus an effect that causes an increase in discharge coefficient will result in an under reading of flow if the coefficient is not corrected.*

Although the design, installation, operation and maintenance of orifice plate metering systems are covered by the ISO 5167:2003 standard, evidence from various studies [2-5] has shown that contamination of the orifice plate results in the metering system operating outside this standard. Quantification of any error produced should be made by reference to the BS ISO TR 12767:1998.standard. The supporting experimental evidence for BS ISO 12767:1998 suggest meter errors ranging up to 24% for various degrees of contamination.

There is a strong indication from the BS ISO 12767:1998 standard and from other reported studies that non gaseous orifice plate contamination results in a meter under registration. However it is not possible to use these studies directly to quantify the measurement uncertainty due to orifice contamination, as they do not collectively cover the typical operating conditions of the NTS hence the work described in this paper.

3 RE-EXAMINATION OF PREVIOUS WORK IN ISO 12767

A considerable amount of work has been carried out on orifice-plate meters in order to determine the effect of non-conformity of these systems and this work was compiled and fed into ISO TR 12767. Deviations from the conditions specified in ISO 5167 are described in this document, in terms of changes in discharge coefficient of the meter. The deviations can be categorised into construction, installation and operation.

Construction of the orifice-plate is very important and any deviation from the standard will lead to changes in the discharge coefficient. For example, orifice-plates that do not have the specified sharpness on the inlet edge, in accordance with ISO 5167, will have progressively increasing discharge coefficients (flow under-registration) as the edge radius increases.

Excessive roughness of the orifice-plate upstream face also lead to an increase in the discharge coefficient with these errors being significant for large beta orifice-plate meters. Errors in the internal diameter of the upstream meter-tube measurement, or meter-tube and orifice bore dimensions wrongly entered into the flow computer, will also introduce flow measurement errors.

ISO TR 12767 states that the effect of deposits on the upstream face of an orifice-plate will impact on the discharge coefficient in a similar way to that of upstream face roughness. The degree of the effect would depend on the degree of fouling and this is shown in Table 1 below. The figure shows the effect of uniform sand particles and the effect of idealised grease spots on an orifice-plate in a 4” (100mm) diameter meter-tube, measuring air at atmospheric pressure. It should be recognised that many of the patterns below do not represent actual observed contamination.

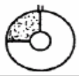
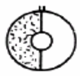
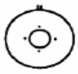
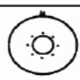
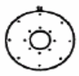
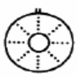
Deposit			Change in discharge coefficient	
			β = 0,2 %	β = 0,7 %
Sand	1 sand quadrant		+ 1,0	+ 0,8
	2 sand quadrants		+ 2,8	+ 1,9
	3 sand quadrants		+ 3,9	+ 2,4
	4 sand quadrants		+ 6,2	+ 3,0
	4 sand quadrants with 6 mm ring removed from around orifice bore		+ 0,3	+ 0,3
Grease	4 grease deposits		+ 1,0	+ 0,1
	8 grease deposits		+ 2,8	+ 1,3
	16 grease deposits		+ 2,1	+ 1,2
	32 grease deposits		+ 2,6	+ 0,6

Table 1. Effect of Deposits on Orifice Plates

Initial work undertaken by Advantica [7] replicated the majority of the configurations in Table 1 using 12” (300mm), rather than 4” orifice plates with the tests being undertaken using natural gas at 55 bar. Typical errors observed where less than half those given in ISO 12767. However, several tests undertaken using different grease patterns indicated higher errors. It was also recognised that the idealised contamination patterns used in ISO 12767 did not represent actual contamination. It was therefore agreed to undertake a larger test programme testing with what where considered to be more realistic contamination patterns and materials. As the programme progressed it was modified to address a wider range of materials and patterns.

4 EXPERIMENTS

The objective of the experiments was to undertake a research programme to establish the impact of more realistic fouling of the upstream face of the orifice-plates under normal operating conditions. In the programme over sixty tests were undertaken.

4.1 Experimental Set Up

The experiments were carried out on using a dedicated test rig at the Advantica Flow Centre at Bishop Auckland, constructed to comply with ISO 5167 as shown in Figure 1 below. Natural gas at the Flow Centre’s prevailing pressure (normally 55 bar) was drawn through a reference turbine meter and then the orifice meter, as shown. The 12-inch turbine meter was installed approximately 40 pipe-diameters (40D) upstream of the orifice-plate. A tube bundle flow straightener was installed upstream of the turbine meter to provide a fully developed flow profile for the gas as it entered the reference meter. 40D of straight pipe between the turbine meter and the orifice-plate allowed the flow to become fully developed again. An additional tube bundle flow straightener was installed between the turbine meter and the orifice-plate at a distance of 13.2 diameters upstream of the orifice-plate.

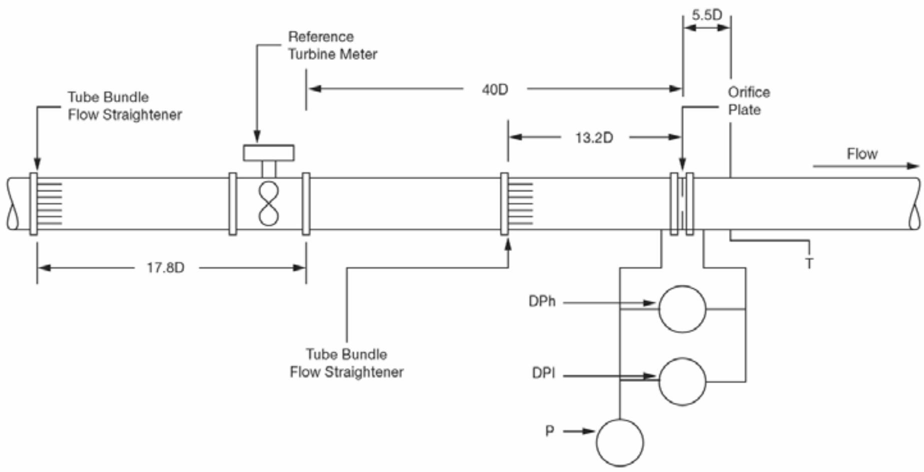


Fig. 1 Layout of Pipework and Instrumentation for Orifice-plate Contamination Project

The differential pressure across the orifice-plate was measured, using two Yokogawa differential pressure transmitters, high and low range. A gauge pressure transmitter was also installed on the upstream of the orifice-plate to record the line pressure immediately before the plate. A temperature transducer was installed 5.5D downstream of the orifice-plate, the readings of which were then corrected to upstream conditions.

The installation of the pressure and differential pressure transmitters (Figure 2) and the impulse lines were in accordance with current standards and best practice, and were calibrated prior to all the tests described below and checked before and after the impulse lines tests.

Three square-edge orifice-plates, with beta ratios of 0.57, 0.6 and 0.7 were manufactured from 6 mm (¼ inch) thick AISI 316 stainless steel, in accordance with ISA RP3.2 and ISO 5167, and used for the experiments. During the experiments, these were sandwiched between two AISI 316 stainless steel carrier-rings, as shown in Figure 3, although in the experiments the tappings where actually located on the side of the holder. The three plates were chosen as they represented commonly used orifice plates within the NTS and the 0.7 beta ratio plate providing a comparison with the work used to produce ISO 12767.

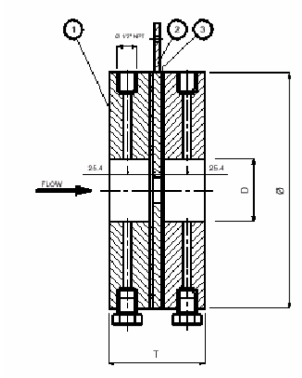


Fig. 2 Instrumentation installation **Fig. 3 Carrier-ring and orifice-plate assembly**

4.2 Test Procedures

The clean uncontaminated metering system was initially calibrated at different flow-rates, corresponding to typically 10, 100, 250, 400, 580 & 750 mbar differential pressures (Reynolds Numbers up 20 million) and these flow rates were then used for the subsequent contamination test series.

The flow-rate at each differential pressure was measured for a period of 100 seconds to give the required resolution. This was repeated twice more and the three sets of flow measurements were averaged to provide the final result. All data was recorded using a data logging system using LabView. Each set of six flows took approximately two hours to undertake, covering flowing time and re-setting of the flow conditions.

Following this calibration, the orifice-plate carrier-ring assembly was removed, disassembled, re-assembled and re-inserted, and then a set of validation measurements was made. This was to demonstrate that no error was introduced due to the orifice assembly process.

For the contamination tests, the orifice plate was removed from the carrier and moved into a laboratory area where contamination was added with the plate in a horizontal position. It was then moved to a vertical position to allow any liquid to drain off before being re-inserted into the carrier in the test line. Placing of contamination on the plate and flow testing were undertaken in one day. Contamination mixtures where made in batches with fluid ratios being created by volume.

4.3 Clean Plate Flows

All plates were calibrated as clean in stable pressure and flow conditions at six different Reynolds numbers representing differential pressures across the plates of between 10 and 750 mbar. To ensure reproducibility of the data a number of clean tests were repeated at the start of the test programme. Further tests where undertaken as the programme progressed to assess whether there was any change in the orifice plate performance. Figure 4 shows the data from six repeats on the 0.7 beta plate. There is excellent repeatability between the data and similar results were obtained for the other plates.

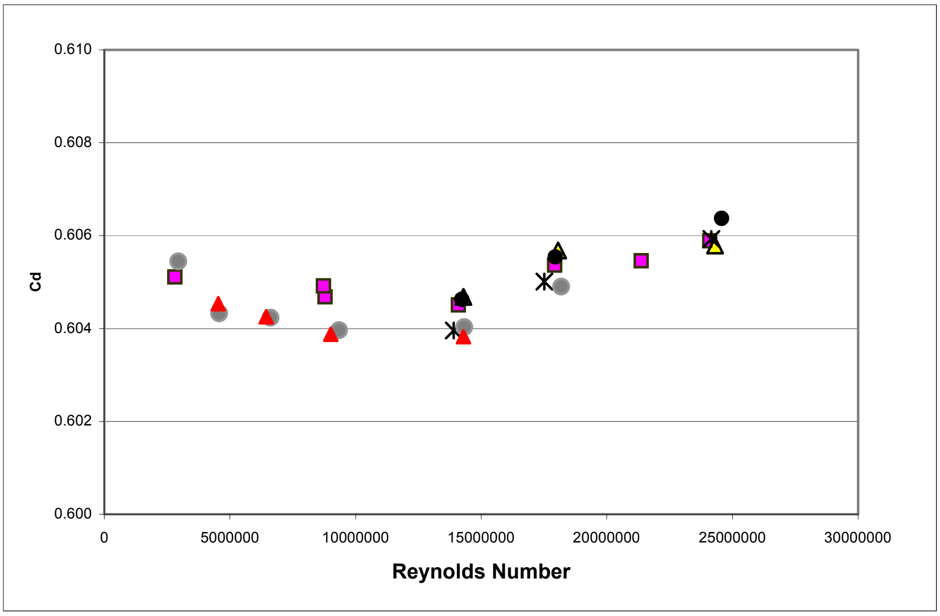


Fig. 4 Discharge coefficient for 0.7 beta ratio plate with repeat tests

4.4 Orifice-plate Fouling

This part of the programme examined the effects of orifice plate contamination on measured flow rate using oils and greases normally associated with the operation of the NTS. Parameters considered included the effect of contamination type, coverage and thickness flow.

Three primary coatings were used; compressor oil, compressor grease (Newman Type 17) and Audco grease, a heavier grease. The majority of the tests where undertaken with Audco grease alone or with Audco mixed with differing ratios of oil (by volume). In most tests the whole of the plate face was covered with the appropriate coating. Variations included changing the coating thickness, either uniformly over the surface or by tapering. Several tests where also conducted with a clean ring around the inner edge of the plate and with contamination on the rear of the plate, a condition not addressed in ISI 12767.

The tests were normally conducted by ramping the flow rate across a range of measured differential pressures, hence Reynolds Number (Re), to a maximum and then ramped back down to the starting conditions. The results from each test were plotted in terms of Reynolds Number (Re) against the shift in flow measurement, rather than discharge coefficient, against the clean plate reference conditions. A typical curve is shown in Figure 5, for a plate covered with 1.2mm of Audco grease, with the maximum under registration being recorded during the ramping up phase whereupon there is little or no change in the measured under registration on the ramping down phase. For this effectively base test, a number of runs where undertaken to assess the reproducibility of the results. The under registration level recorded during the ramp down is defined as the saturation level, that is, if no further plate contamination occurred, this would be the continuous level of under registration expected until the operating conditions or contamination levels changed. The area enclosed by the saturation and maximum shift data of the flow curve represents a typical range of under registration a contaminated meter system would be expected to exhibit over its flow range. A continuously contaminated meter would under register towards the maximum shift line, where as a single contamination incident would see a range of under registration bounded by the envelope as shown. Of the coatings tested, the Audco grease was most resistant to removal during the flow period. For lighter materials such as oil and compressor grease cleaning of the plate was more prominent and the saturation level was lower relative to the maximum shift data (Figure 6).

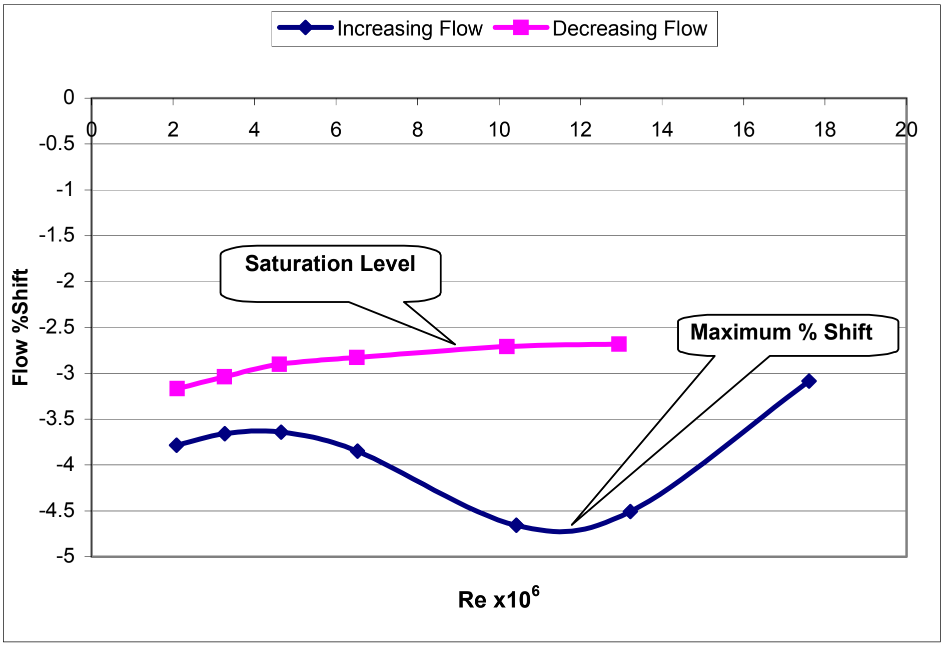


Fig. 5 Typical Test Curve (heavier coating, 1.2mm of Audco grease full coverage front face)

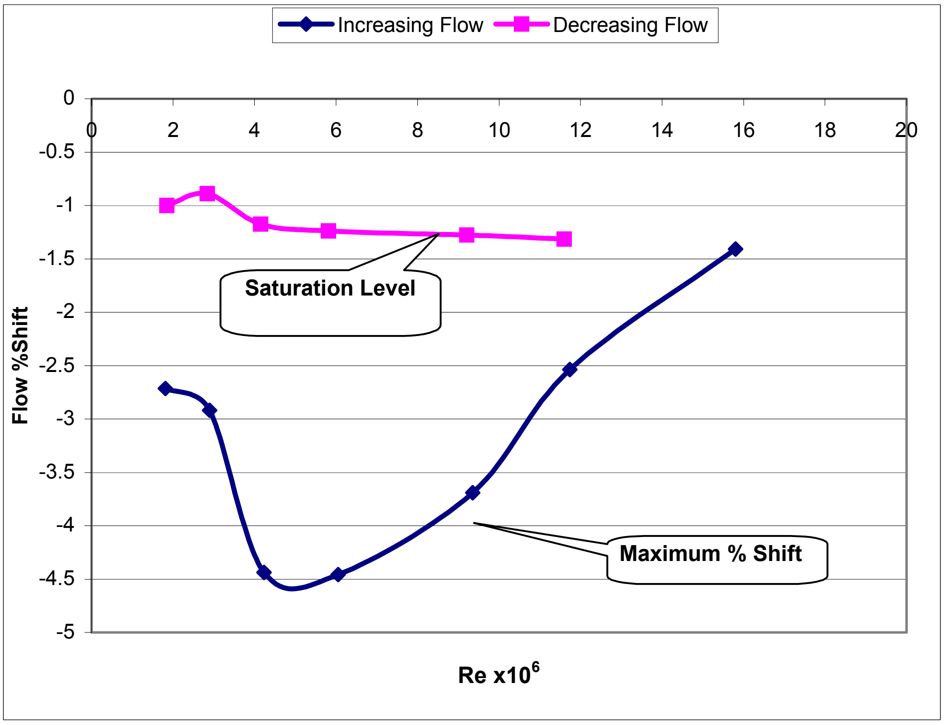


Fig. 6 Typical Test Curve (lighter coating, 1.2 mm of 80% Audco grease/ 20% oil full coverage front face)

The curves presented in Figures 5 and 6 are typical of those observed in all tests where the flow was ramped up and then down. For the rising flows the maximum shift in flow relative to the reference was seen at between 25% and 50% of the full flow range of the plate. The decrease in shift beyond this is believed to be due to cleaning of the plate. For the falling flows most tests resulted in an almost constant shift represented by a horizontal curve.

It should be noted that in the test programme clean fluids where used and these especially the lighter fluids where prone to be cleaned off the face of the plate by the flowing gas. Observation of actual contamination on orifice plates indicates that some types of contamination can remain on the plate surface despite the gas flow and there may be a number of reasons for this depending upon the actual contamination and the operating conditions of the plate. As such the Audco grease tests where considered to best represent permanent contamination conditions.

4.4.1 Effect of Beta Ratio and Contamination Area

Initial tests indicated that for a given coating, the observed error was higher for the smaller beta ratios, e.g. with compressor grease the maximum shift or under-registration in flow was 2.8% for a 0.6 beta ratio plate and 2.3% for a 0.7 beta ratio plate.

A number of 0.6 beta ratio tests where undertaken with only two quadrants of the plate covered with 1.2mm of Audco grease. For either the bottom two or top two quadrants covered the maximum shift in flow rate was 1.6% compared to 4.5% when the whole plate was covered. However, with two quadrants nearest the side tappings being coated the maximum shift was 2.2% whereas the shift was 3.7% when the two quadrants furthest from the tappings were coated.

A further test was undertaken with a 10mm clean ring around the inner edge of the 0.6 beta ratio plate. This test effectively assessed the contribution to error from contamination near the plate bore. For this test the maximum shift in flow rate was 1.0% compared to 4.5% for the completely covered plate. A ring of 20mm width resulted in a shift of only 0.5%. This suggests that most of the shift in flow rate is caused by contamination near the bore of the plate.

The standard ISO 12767 does not address the effect of contamination on the back of a plate. For compressor grease, 1.2mm on the front plate resulted in a maximum shift of 2.8%. A similar thickness only on the back of the plate resulted in a shift of 0.5% whereas with 1.2mm on the front and back the maximum shift was 3.3%. Consideration should be given to contamination on the rear of the plate as experience has shown that contamination passing through the plate bore can end up on the rear of the plate.

A test was also undertaken with a tapered coating with 1.2mm thick Audco coating at the outer edge of the plate tapering to 0mm at the bore. This configuration resulted in a flow rate shift of 1.3%.

4.4.2 Effect of Contamination Type

The test programme encompassed a number of contamination types as discussed in Section 4.4 above. Initial work was undertaken with compressor grease but the majority used Audco grease alone or in a mixture with oil. Results from five different contamination types are shown in Figure 7 where saturation levels are plotted against Reynolds numbers.

For the Audco grease the saturation level flow shift is approximately 3% whereas the Audco/Oil mixtures and the lighter compressor grease have flow shifts of between 0.4% and 1.4%. The test involving only oil resulted in little or no shift in the flow relative to the reference figures. Indeed in the rising run of this test the shift in flow was positive and effectively the saturation level represents a clean plate as the oil was removed from the plate surface quite by the flowing gas.

There is indication from these five tests that the shift in flow is due to the type of contamination and its effectiveness in remaining on the surface of the plate.

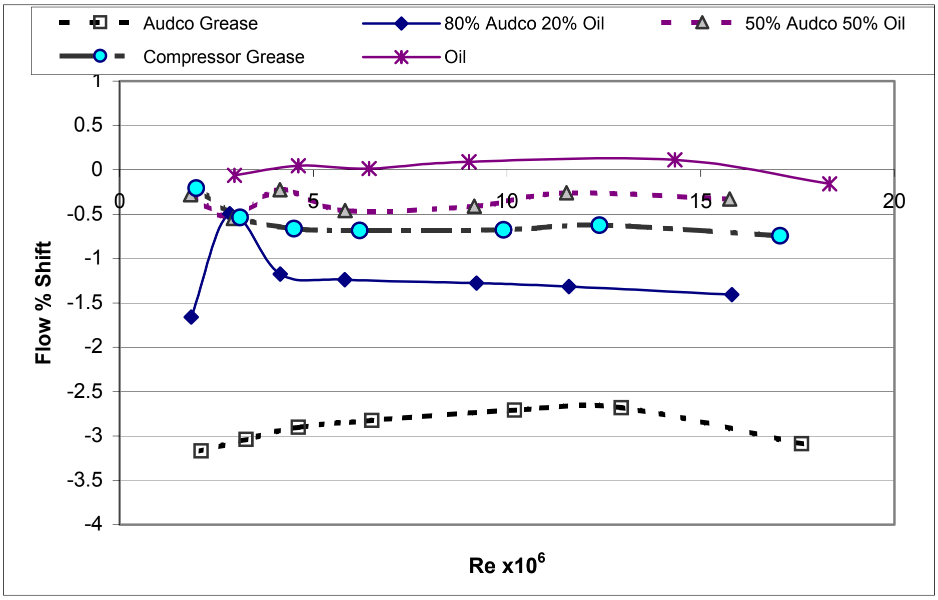


Fig. 7 Comparison of saturation levels for different contamination types (1.2 mm coating)

4.4.3 Effect of Contamination Thickness

The effect of contamination thickness was also assessed and the results from a series of tests involving Audco grease are plotted in Figure 8 with saturated levels plotted against Re.

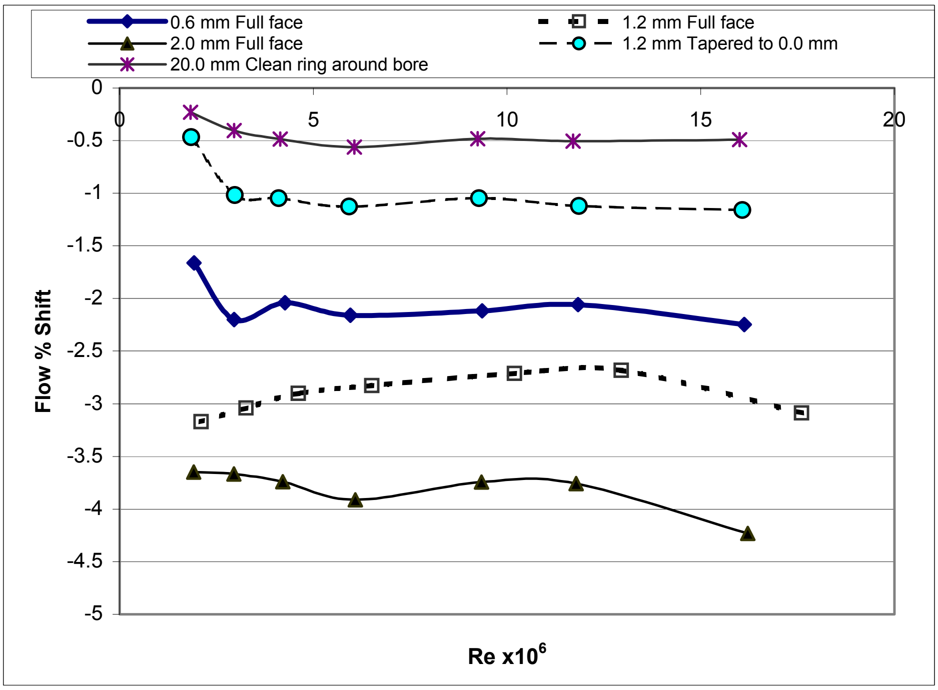


Fig. 8 Comparison of coating thickness/pattern saturation levels for Audco grease

For the three tests with full plate coverage the saturation levels are related to the contamination thickness with the flow rate shift varying from 4% for a 2mm coating to 2% for a 0.6mm coating. The last two tests with a tapered coating and a clean ring show much shower shifts and appears to show that much of the shift seen is due to contamination at the bore of the plate.

The key results from the front face contamination tests undertaken are summarised in Table 2. The table presents average saturation level shifts together with the maximum observed shift and the Reynolds Number at which this occurred. For the 1.2mm full front face Audco grease contamination a further test was undertaken at 38 bar and compared with the test at 55 bar. There are small differences in the flow shift seen and there is a suggestion that a higher pressure results in lower flow errors.

Test Type/Material	**% Shift (Saturation)**	**% Shift (Re) (Maximum)**
Clean Plate	0	-0.3
Clean Ring 200mm (Audco Grease)	-0.5	-0.5 (6×10^6)
0.6mm Full Front Face (Audco Grease)	-2.00	-2.00 (12×10^6)
1.2mm Full Front Face (Audco Grease)	-2.25 (38 bar) -2.00 (55 bar)	-3.90 (6×10^6) -3.30 (5×10^6)
2.00mm Full Front Face (Audco Grease)	-4.0	-5.00 (12×10^6)
1.2mm Front Face Taper (Audco Grease)	-1.0	-1.30 (5×10^6)
1.2mm Full Front Face (Valve Grease)	-1.00	-2.80 (6×10^6)
1.2mm Full Front Face (80:20 Audco:Oil)	-1.0	-4.00 (4×10^6)
1.2mm Full Front Face (50:50 Audco:Oil)	-0.25	-0.90 (2×10^6)
0.6mm Full Back Face (80:20 Audco:Oil)	-0.1	-0.40 (4×10^6)
1.2mm Full Front Face (Oil)	+0.1%	+0.24% (18×10^6)

Table 2. Summary of Front Face Contamination Studies

5 DISCUSSION

From the results obtained an attempt has been made to determine a physical characteristic of contaminate that correlates to the measurement shift observed. Viscosity of contaminate has been identified and a quantification of the maximum and minimum measurement shift in terms of a normalised viscosity at an initial coating thickness of 1.2mm made. This analysis is presented in Figure 9.

The viscosity analysis can be summarised as follows:

- Coatings with high viscosity (such as Audco Grease without oil) do not exhibit significant visual orifice plate cleaning and record the largest under registration of flow (saturation level) (~ -2.00%).

- Coatings with reduced viscosity levels (such as blends of Audco and Oil or Valve Grease) show significant orifice plate cleaning at the bore and record lower saturation under registration levels.

- There appears to a consistent behaviour between the saturation levels and viscosity with lower under registration being recorded as the viscosity of the coating decreased.

- The temperature dependence of the saturation level was examined using orifice plates coated in the 80:20 blend of Audco Grease and Oil over two temperature ranges. The results from these tests revealed that as the temperature increased the maximum under registration decreased, although the saturation levels over both temperature ranges were not significantly different (~ -1.0%). The maximum under registration occurred between Reynolds Numbers of 4×10^6 and 6×10^6, which was consistent with the other tests on coatings of a similar thickness (1.2mm).

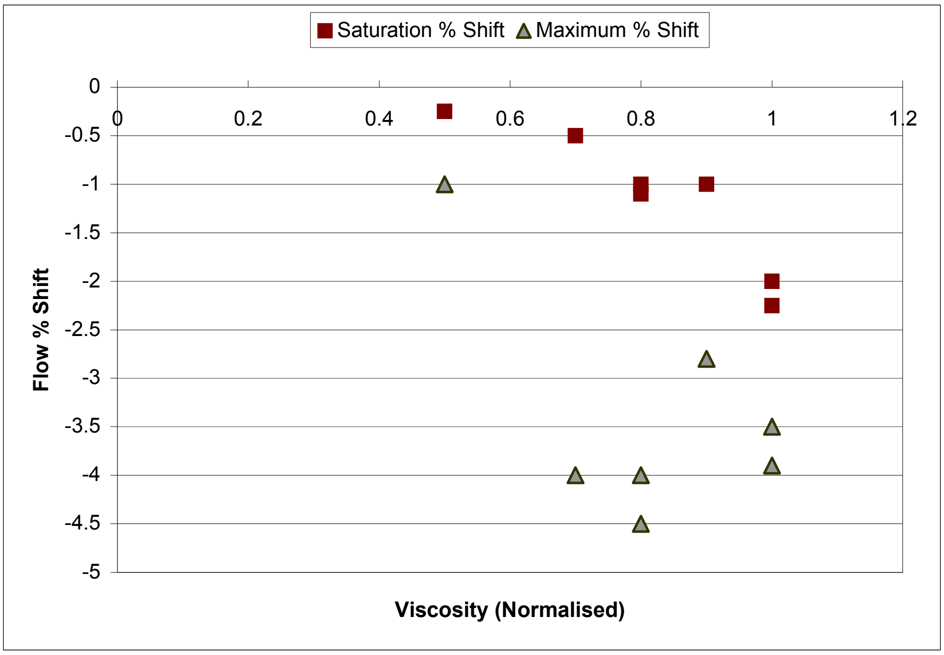


Fig. 9 Maximum and saturation measured shift with normalised viscosity

The use of viscosity as a term of reference to quantify meter plate contamination is considered justified as:

- Any contamination of the plate (on the up or down stream face) produced meter system under registration.

- Under registration was always recorded if there was any contamination on the front face of the plate even if the bore area was clean and stayed clean during the test. Thus under registration can be considered to be a function of the condition of the whole plate, not just the condition about the bore.

- Decreasing viscosity resulted in plate cleaning with contaminant either being redistributed about the orifice plate or being drawn through the bore. Low viscosity coatings exhibited low levels of contaminant at the bore resulting in low saturation under registration values. In some instances there was evidence of reverse plate contamination as the coating had been sufficiently viscous to be redistributed from the front face but in so doing had become entrained on the reverse (downstream) face.

- The test with a tapered coating exhibited a slightly higher saturation under registration level (-1%) than the lower viscosity coatings (-0.5%). The coating morphology was not significantly altered during the test (no bore cleaning) although the maximum (-1.3%) and saturation (-1.0%) under registration were similar.

From the analysis presented it is reasonable to assume that the reduction in saturation under registration was due to the contaminant being removed or redistributed around the bore. However, higher levels of saturation under registration are recorded if the area adjacent to the bore remained contaminated during the test.

The state of the bore is considered significant, as low viscosity coatings are likely to be redistributed about the plate, either being continuously removed or adopting a fixed morphology on the plate surface. In the former case, if the contamination was not being replenished, the under registration (saturation level) could be expected to reduce to near constant value, approximating to that of a clean or near clean plate. In the case where the coating adopts a fixed morphology, or where the coating material is being continuously deposited, the under registration level is again likely to be constant but of a greater magnitude

6 CONCLUSIONS

Contamination on the orifice plate front face does lead to metering error and an under registration of gas flow.

Evidence shows that contamination can move over the surface of the orifice plate leading to a saturation level of under registration, this being the level that would exist after a period of gas flow and is considered a steady state condition. This would exist in cases where there was no continuous contamination scenario.

In general, it was found that the condition of the bore of the orifice plate was very significant. In cases where the contaminant morphology was being continuously redistributed at the bore (Audco Grease – full face) the highest levels of saturation under registration were recorded.

7 NOTATION

C	Discharge coefficient
q_m	Mass rate of flow
d	Diameter of orifice-plate bore
D	Internal upstream meter-tube diameter
Re	Reynolds Number
β	Diameter ratio (=d/D)
$\Delta\rho$	Differential pressure
ε_1	Expansibility factor at the upstream tapping
ρ_1	Fluid density at upstream pressure tapping

8 REFERENCES

[1] BS EN ISO 5167 Parts 1 & 2: 2003, Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full.

[2] GRI Report 00/0141, Metering Research Facility Program: Operational factors that affect orifice meter accuracy.

[3] N.B. Lansverk, Effects of abnormal conditions on accuracy measurement, Trans. Florida Gas. 1984

[4] J.N. Witte, Proper orifice meter test must include plate tube inspection, 1999 (web: www.pipe-line.com)

[5] V.C.Ting, Effects of non-standard operation conditions on the accuracy of orifice meters. S.E.P 22867. 1991

[6] ISO TR 12767:1998. Measurement of fluid flow by means of pressure differential devices – Guidelines to the effect of departure from the specifications and operating conditions given in ISO 5167-1. (Also BS ISO TR 12767:1998)

[7] M. Pritchard, A. Niazi, D. Marshall, Assessment of the effect of contamination on orifice plates, 11th Flomeko, 12-14 May 2003

[8] AGA Report No.3 1992, (AGA3) Orifice metering of natural gas.