Wedge Meters with Low Reynolds Number Flow

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Abstract

CEESI calibrated 8” wedge & cone meters across a low Reynolds number range on the new CEESI oil flow laboratory. This data was compared to similar 3rd party 8” Venturi meter data. The data sets are compared and the problems of flow metering at low Reynolds numbers discussed. All meters were tested with the DP Diagnostics DP meter diagnostic system “Prognosis” installed. It is shown that once fully calibrated to be diagnostic ready, each meters Prognosis system could tell the operator the fluid viscosity, and hence the Reynolds number, discharge coefficient and flow rate.

1. Introduction

Flow measurement of high viscosity oils is an important and challenging area for the future of the energy sector. The vast majority of the world’s oil reserves are classed as high viscosity (i.e. ‘heavy’) oil. Not only are there difficulties in the extraction and transportation of these fluids, but high accuracy flow measurement has also been proven to be extremely problematic.

As Reynolds number increases the velocity profile moves from a laminar flow profile, to one transitioning between laminar and turbulent, to fully turbulent flow. High viscosity oil flows have Reynolds number ranges that straddle this varying flow profile region. Therefore before calibration many flow meters have unpredictable performance at low Reynolds numbers. As such it is highly adviseable to calibrate many flow meter designs before use in heavy / highly viscous oil applications.

CEESI has developed an oil test facility for heavy oil / high viscosity flow meter calibration. As part of the commissioning of this facility an 8”, 0.707 beta wedge meter was tested across a wide range of Reynolds numbers. The wedge meter was chosen as it is marketed as having a constant discharge coefficient across a wide Reynolds number range, i.e. a steady predictable performance (i.e. discharge coefficent) across a range of high viscosity oil flows. It is claimed it is immune to flow profile changes. If this was true, it would offer significant benefits over competing meter designs. Prevention is better than cure. A constant wedge meter discharge coefficient would be independent of Reynolds number and therefore there would be no need for the operator to data fit a possibly relatively complex discharge coefficient to Reynolds number relationship. Also, there would be no need for the operator to know the oil viscosity in the field in order to predict the associated Reynolds number, and hence the flow rate prediction.

NEL & DP Diagnostics [1] have previously published Venturi meter high viscosity data. Therefore, in order to further advance industries knowledge of the effect of high viscosity flows on DP meters, CEESI also tested a standard 8”, 0.75 beta cone meter across a low Reynolds number range. This paper compares these Venturi, cone, & wedge meter data sets and discusses performance when in use in low Reynolds number applications.

DP Diagnostics worked with both CEESI and NEL to show how their DP meter diagnostic system (“Prognosis”) operates with high viscosity flow. It is shown that once the DP meter is calibrated to find the Reynolds number vs. discharge coefficient & diagnostic parameter relationships, then the diagnostic system can tell the operator the viscosity, Reynolds number, and hence the discharge coefficient and flow rate without the viscosity being needed to be supplied from an external source. This can allieviate the significant practical field problem of the operator not knowing the fluid viscosity at any given time.

2. DP Meter Operation

Equation 1 shows the generic DP meter mass flow equation, where m is the mass flow rate, E & A_t are constant geometry terms, ρ is the fluid density, & ΔP_t is the traditional DP primary signal. The discharge coefficient (C_d) is found by data fitting the calibration results to some function (f) to the Reynolds number, see equation 2. Equation 3 shows the Reynolds number expression, where D is the meter inlet diameter and μ is the fluid viscosity.

$$m = EA_t C_d \sqrt{2\rho \Delta P_t} \quad (1)$$

$$C_d = f(\mathrm{Re}) \quad (2)$$

$$\mathrm{Re} = \frac{4m}{\pi \mu D} \quad (3)$$

Hence, the mass flow rate is found by iteration across equations 1, 2, & 3. The operator supplies the fluid density and viscosity from an external source. However, when metering highly viscous (‘heavy’) oil flow the viscosity is often not known to a low uncertainty. An oil’s viscosity can change significantly with relatively small changes in composition and temperature. The viscosity significantly influences the Reynolds number which in turn influences the DP meter’s discharge coefficient and therefore the flow rate prediction. To compound the problem of not always knowing the viscosity to a low uncertainty, at low Reynolds number flows DP meter discharge coefficients tend to be very sensitive to Reynolds number. At low Reynolds number flows an erroneous viscosity keypad entry can therefore produce a significant Reynolds number, discharge coefficient and therefore flow rate prediction error.

It is important for a DP meter for use in a high viscosity oil flow application to be calibrated across the application low Reynolds number range, and for the discharge coefficient vs. Reynolds number relationship to be appropriately defined (i.e. equation 2). It is also important for the viscosity to be known accurately.

3. Venturi, Cone and Wedge Meter Low Reynolds Number Data Sets

In 2014 NEL and DP Diagnostics published low Reynolds number range 4" & 8", 0.6β Venturi meter data (Rabone et al [1]). This added to an earlier publicly available ConocoPhillips (CoP) 4" Venturi meter data set. (The authors do not know the beta or test facility used by CoP). CEESI has some archived low Reynolds number mineral oil flow data from orifice meters. Now CEESI and DP Diagnostics extend the published data with 8", 0.707β wedge meter and 8", 0.75β cone meter low Reynolds number data sets.

Fig 1. Clockwise from top, NEL 8" Venturi meter, & CEESI 8" wedge meter & 8" cone meter.

Figure 1 shows three of these DP meters under test. Oil flow test facilities can choose to run with different oil grades. For these data sets CEESI used Exxsol D80 (2cP), Drake Oil 5 (15cP), & Drakeoil 32 (175 cP) at ambient temperature. The NEL data is from three oils stated to have a viscosity of 87cP, 187cP, & 536cP respectively.

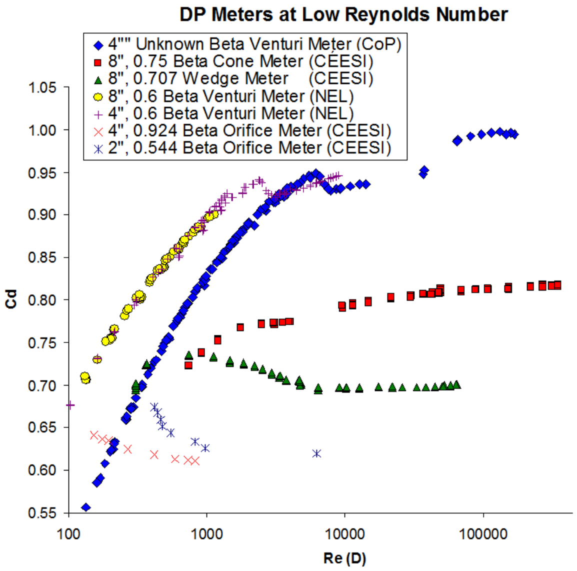

Fig 2. DP meter low Reynolds number data

Figure 2 shows high viscosity low Reynolds number DP meter data. Moderate to high Reynolds number flows, where most flow meters are used, produce Venturi, cone, wedge & orifice meter discharge coefficients of approximately 1, 0.8, 0.7, & 0.6 respectively. That is, across common Reynolds number ranges where DP meters are usually operated, respective DP meter discharge coefficients are rather constant, with Reynolds number only having a second order influence on the discharge coefficient. Figure 2 shows that as the Reynolds number increases the DP meter discharge coefficients are tending to these expected relatively constant values. However, it is also evident that as the Reynolds number reduces (into the turbulent to laminar flow profile region) the influence of Reynolds number on the discharge coefficient becomes very pronounced. It is therefore very important to calibrate a DP meter's discharge coefficient vs. Reynolds number relationship across the applications Reynolds number range.

The CoP and NEL Venturi meter data sets are in general agreement. At some threshold minimum Reynolds number value the Venturi meter discharge coefficient begins to reduce. The change is not particularly linear with humps evident in two Venturi meter data sets. If we consider the normal moderate to high Reynolds number range Venturi meter discharge coefficient of 1, then we see the Venturi meter discharge coefficient can drop to between 0.7 & 0.55 at very low Reynolds numbers, i.e. a discharge coefficient reduction up to -40%. Even with a precisely known viscosity, calibration and appropriate data fitting to predict this would be essential to achieving low uncertainty flow metering.

The CEESI orifice meter data sets show that the meters have the expected discharge coefficient at moderate flow rates, i.e. approximately 0.6. As the Reynolds number reduces below some threshold value both orifice meter discharge coefficients begins to increase. The two orifice meter discharge coefficients increase from 0.6 to 0.64 &

0.67 at very low Reynolds number, i.e. a discharge coefficient increase of approximately +7% & +12%. Again, even with a precisely known viscosity, calibration and appropriate data fitting to predict this would be essential to achieving low uncertainty flow metering.

The CEESI cone meter data shows that the higher Reynolds numbers gave the expected discharge coefficient of approximately 0.8. However, as the Reynolds number reduces and the velocity profile changes the discharge coefficient reduces down to about 0.7, i.e. a reduction of -12%. Unlike the Venturi meter data sets this single cone meter data set had a relatively smooth / linear change in discharge coefficient. Again, even with a precisely known viscosity, calibration and appropriate data fitting to predict the Re vs C_d relationship would be essential to achieving low uncertainty flow metering.

The claim of some wedge meter proponents has long been that the wedge meter discharge coefficient is constant across a very wide range of Reynolds numbers. If the wedge meter did have a constant discharge coefficient across a very wide range of Reynolds numbers, a higher Reynolds number range calibration (say in a water flow laboratory) would suffice as this calibration result could then be extrapolated with confidence down to lower oil flow Reynolds number ranges. If true this would offer a significant advantage over other DP meters in low Reynolds number applications. A less expensive and easier water flow calibration, instead of an oil flow calibration, would suffice to find the wedge meter discharge coefficient for the lower Reynolds number range of an oil flow. Also, if the discharge coefficient was a constant value, and therefore not fitted to the Reynolds number, it would be independent of viscosity. Therefore there would be no necessity for the end user to know the fluid viscosity in order to calculate the Reynolds number and then the discharge coefficient.

However, Figure 2 shows that in reality the wedge meter discharge coefficient is influenced by the Reynolds number. The CEESI wedge meter data shows that the higher Reynolds numbers gave the expected discharge coefficient of approximately 0.7. However, as the Reynolds number reduced below a threshold of about 6,000 the discharge coefficient begins to change, first rising to 0.72 at 2,000 Reynolds number, before falling to 0.683 at 300 Reynolds number. That is, within the range of $300 \leq Re \leq 6,000$ the wedge meter discharge coefficient rises approximately by +3% and then drops by -2.5%. Although this is a smaller change than seen for the other DP meter designs tested, considering heavy oil flow is high value flow, these variances are rather high to ignore. For ≤ 1% allocation or fiscal metering of highly viscous oil flow a wedge meter must be calibrated across the applications Reynolds number range just like other DP meters.

Although the wedge meter tested was found to be influenced by the Reynolds number, the wedge meters discharge coefficient was more resistant to the effects of Reynolds number than the other DP meters tested. The wedge meter discharge coefficient did not become very sensitive to Reynolds number until a much lower Reynolds number value than the other DP meters. Furthermore, the fluctuation of the discharge coefficient was, while significant, less than the other DP meters tested. There is therefore possibly a grain of truth in the claim that the wedge meter has a constant discharge coefficient across a very wide Reynolds number. However, this is not true for very low Reynolds number flow ranges as found in high viscosity oil flow production. For such applications calibration across the applications Reynolds number range is required.

3. Calibration Practices

When calibrating a DP flow meter the appropriate relationship to consider is the Reynolds number vs. discharge coefficient. There are theoretical reasons for this that are described in Fluid Mechanics text books, but such detail is out with the scope of this paper. It can be relatively expensive to correctly flow test a meter across the applications Reynold number range. It can therefore be economically attractive to use a water flow facility to calibrate the meter over the same velocity / flow range as the application and assume that the meter is correctly calibrated. Unfortunately, this assumption can be incorrect.

A flow meter can only be calibrated with a fluid type different than its application if the calibration data covers the same Reynolds number as the application. It

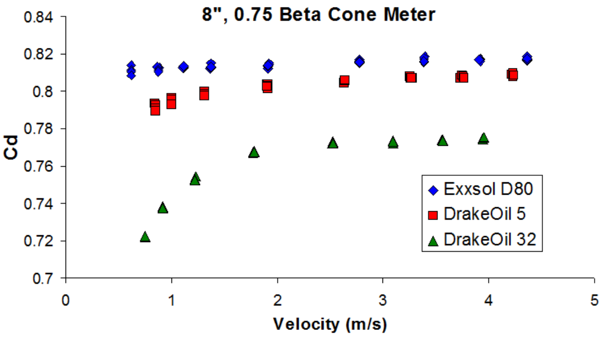

Fig 3. 8” Cone Meter Calibrated to Flowrate/Velocity.

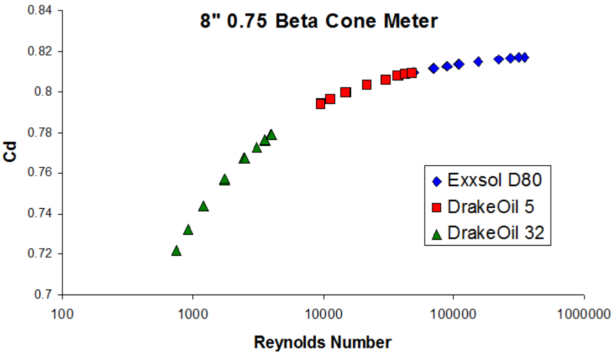

Fig 4. 8” Cone Meter Calibrated to Reynolds No.

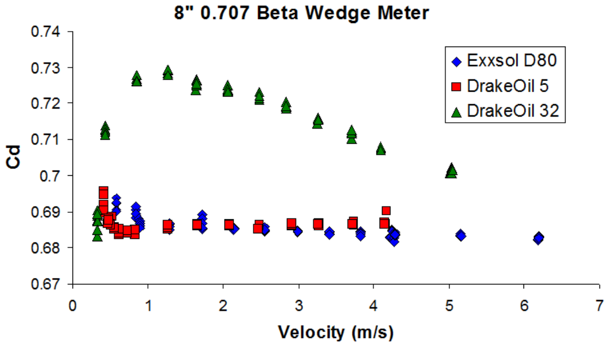

Fig 5. 8” Wedge Meter Calibrated to Flowrate/Velocity.

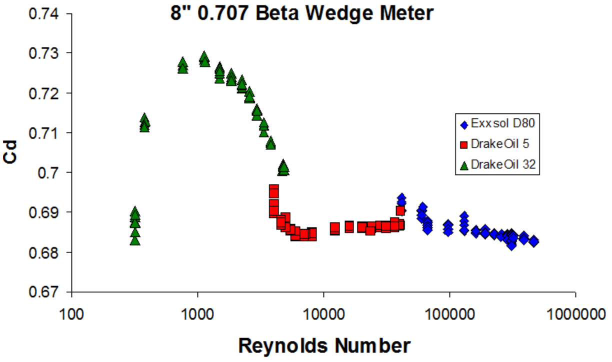

Fig 6. 8” Wedge Meter Calibrated to Reynolds No.

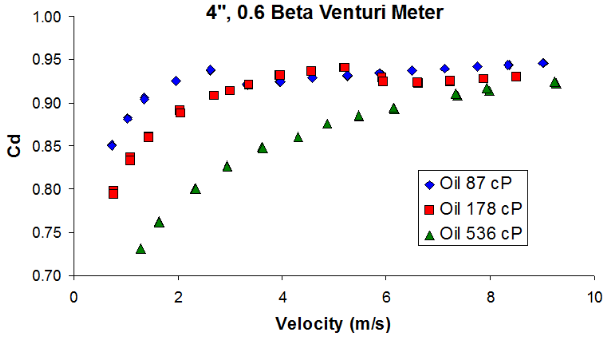

Fig 7. 4” Venturi Meter Calibrated to Velocity.

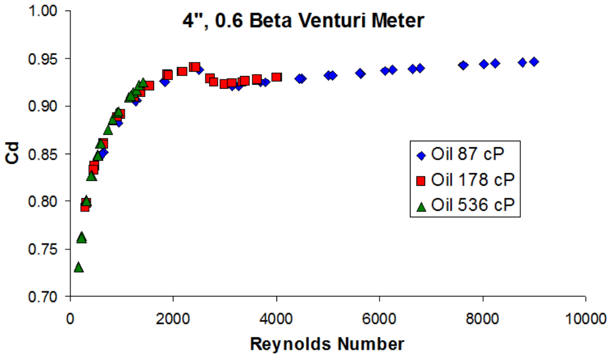

Fig 8. 4” Venturi Meter Calibrated to Reynolds No.

is not good practice to calibrate a flow meter across the same velocity / volume flow rate of the application but a different Reynolds number range.

Figure 3, 5 & 7 show 8” CEESI cone meter, CEESI wedge meter, & NEL Venturi meter calibration data sets respectively. Each meter was calibrated by using three different oils of different viscosity across the same flow rates range. Clearly, the calibration results are quite different depending on the oil viscosity. You cannot chose to calibrate a DP meter with one fluid across a given velocity / volume flow rate and expect that calibration to be applicable to another fluid of different viscosity across the same velocity / flow rate range.

Figures 4, 6 & 8 show the same data as Figures 3, 5, & 7 respectively, only now the discharge coefficient is plotted to Reynolds number instead of velocity / flowrate. Whereas the discharge coefficient vs. velocity / flow rate data looked quite different for the different oils (i.e. different fluid viscosities), plotting the discharge coefficient vs. Reynolds number shows that this perceived difference is actually a Reynolds number effect. This data clearly highlights the importance of calibrating DP meter discharge coefficient to Reynolds number.

4. Calibration is Only Half the Cure

It is essential to calibrate DP meters for use in highly viscous flow metering applications across the applications Reynolds number range. It is then necessary to data fit (or ‘linearize’) the discharge coefficient to Reynolds number relationship. The meter is then said to be appropriately calibrated. However, in the case of ‘heavy oil’ high viscosity applications the operator has one more obstacle to overcome. That is, the operator needs to know the fluid viscosity.

In most flow metering applications, such as gas or water applications, the operator will have a low uncertainty value for the fluid viscosity. However, this is often not true for heavy oil applications. With heavy oil flow metering applications viscosity is far more difficult to know. Slight changes in oil composition and / or temperature can produce significant changes in viscosity. (It is even possible for temperature & hence viscosity gradients across the cross sectional area of the pipe.) Figure 2 shows that the consequence of not knowing the viscosity is far more severe than in most flow metering applications. An erroneous viscosity input produces an incorrect Reynolds number, and associated erroneous flow rate prediction. This is the crux of the heavy oil metering problem. It is extremely important to know the fluid viscosity.

5. The DP Meter Diagnostic System ‘Prognosis’ Used to Estimate Oil Viscosity

DP Diagnostics created a DP meter diagnostic system called ‘Prognosis’. An overview of this ‘pressure field monitoring’ diagnostic system is now given. For details the reader should refer to the descriptions given by Rabone et al [2].

Figure 9 shows a sketch of a generic DP meter and it’s pressure field. The DP meter has a third pressure tap downstream of the two traditional pressure ports. This

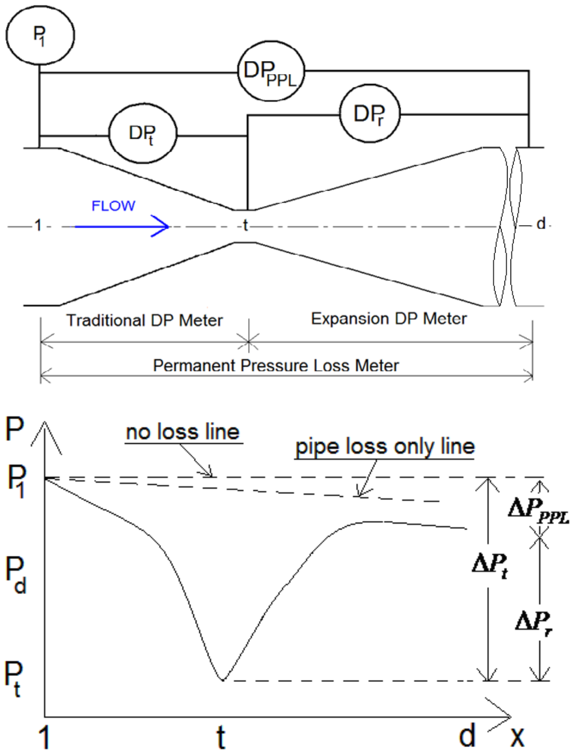

Fig 9. Venturi meter with instrumentation sketch and pressure field graph.

$$\Delta P_t = \Delta P_r + \Delta P_{PPL} \quad \pm\,\theta\% \qquad \text{--- (4)}$$

Traditional flow calculation:

$$\dot{m}_t = EA_t Y C_d \sqrt{2\rho\Delta P_t} \quad \pm\,\text{x\%} \qquad \text{--- (1)}$$

Expansion flow calculation:

$$\dot{m}_r = EA_t K_r \sqrt{2\rho\Delta P_r} \quad \pm\,\text{y\%} \qquad \text{--- (5)}$$

PPL flow calculation:

$$\dot{m}_{ppl} = AK_{PPL} \sqrt{2\rho\Delta P_{PPL}} \quad \pm\,\text{z\%} \qquad \text{--- (6)}$$

allows three DPs to be read, i.e. the traditional (ΔP_t), recovered (ΔP_r) and permanent pressure loss (ΔP_{PPL}) DPs. These DPs are related by equation 4. The percentage difference between the inferred traditional DP (i.e. the sum of the recovered & PPL DPs) and the read traditional DP is *δ%*, while the maximum allowed difference is *θ%*.

Each DP can be used to independently meter the flow rate, as shown in equations 1, 5 & 6. Here $\dot{m}_{trad}$, $\dot{m}_{\exp}$ & $\dot{m}_{PPL}$ are the mass flow rate predictions of the traditional, expansion & PPL flow rate calculations with $x\%$, $y\%$ & $z\%$ uncertainties respectively. *A* is the inlet area and Kr & Kppl are the expansion & PPl coefficients respectively. Comparing these flow rate predictions produces three diagnostic checks. The percentage difference of the PPL to traditional flow rate calculations is denoted as $\psi\%$. The allowable difference is the root sum square of the PPL & traditional meter uncertainties, $\phi\%$. The percentage difference of the expansion to traditional flow rate calculations is denoted as $\lambda\%$. The allowable difference is the root sum square of the expansion & traditional meter uncertainties, $\xi\%$. The percentage difference of the expansion to PPL flow rate calculations is denoted as $\chi\%$. The allowable difference is the root sum square of the expansion & PPL meter uncertainties, $\nu\%$.

Reading these three DPs produces three DP ratios, the 'PLR' (i.e. the PPL to traditional DP ratio), the PRR (i.e. the recovered to traditional DP ratio), the RPR (i.e. the recovered to PPL DP ratio). DP meters have predictable DP ratios. Therefore, comparison of each read to expected DP ratio produces three diagnostic checks. The percentage difference of the read to expected PLR is denoted as $\alpha\%$. The allowable difference is the expected PLR uncertainty, *a%*. The percentage difference of the read to expected PRR is denoted as $\gamma\%$. The allowable difference is the expected RPR uncertainty, *b%*. The percentage difference of the read to expected RPR is denoted as $\eta\%$. The allowable difference is the expected RPR uncertainty, *c%*.

These seven diagnostic results can be shown on the operator interface as plots on a graph. That is, we can plot (Figure 10) the following four co-ordinates to represent the seven diagnostic checks:

$$(\psi\%/\phi\%, \alpha\%/a\%), (\lambda\%/\xi\%, \gamma\%/b\%), \\ (\chi\%/\nu\%, \eta\%/c\%) \;\&\; (\delta\%/\theta\%, 0).$$

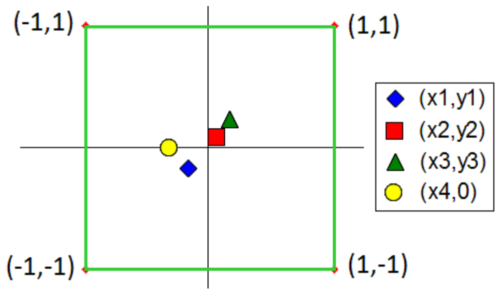

Fig 10. Normalized Diagnostic Box (NDB) with diagnostic results

For simplicity we can refer to these points as (x_1,y_1), (x_2,y_2), (x_3,y_3) & (x_4,0) respectively. The act of dividing the seven raw diagnostic outputs by their respective uncertainties is called 'normalisation'. A Normalised Diagnostics Box (or 'NDB') of corner coordinates (1,1), (1,-1), (-1,-1) & (-1,1) can be plotted on the same graph (see Figure 10). This is the standard user interface with the diagnostic system 'Prognosis'. All four diagnostic points inside the NDB indicate a serviceable DP meter. One or more points outside the NDB indicate a meter system malfunction.

Figure 1 shows a Venturi, cone & wedge meters each with a downstream tap being calibrated to be diagnostic ready. Whereas Prognosis is essentially a generic DP meter diagnostic system to warn the operator of a generic DP meter malfunction, like most instrument diagnostics systems, if the operator has a known *specific* issue it can be directed at monitoring *that* specific issue. Hence, here Prognosis can be set to monitor (and predict) the fluid viscosity.

5a Venturi meter

Figures 11 & 12 show NEL 8”, 0.6β Venturi meter (see Fig. 1) high viscosity data (see Rabone et al [2]). Figure 11 shows three flow coefficients vs. Reynolds number calibration data. Figure 12 shows three DP ratio vs. Reynolds number calibration data. This data was used to calibrate the meter (i.e. Cd vs Re) and the Prognosis system. The Prognosis calibration takes no more effort or expense than using two extra DP transmitters during the standard calibration..

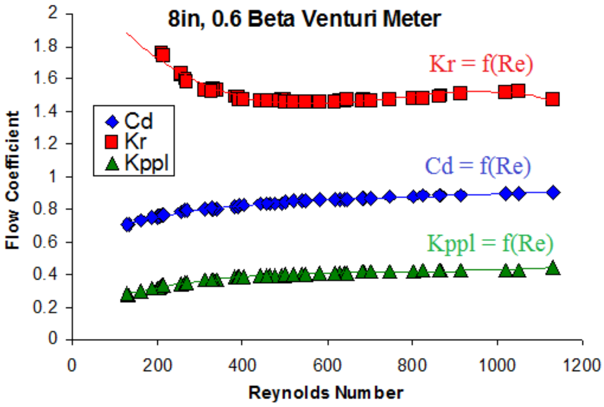

Fig 11. Venturi Meter Flow Coefficients vs. Re. No.

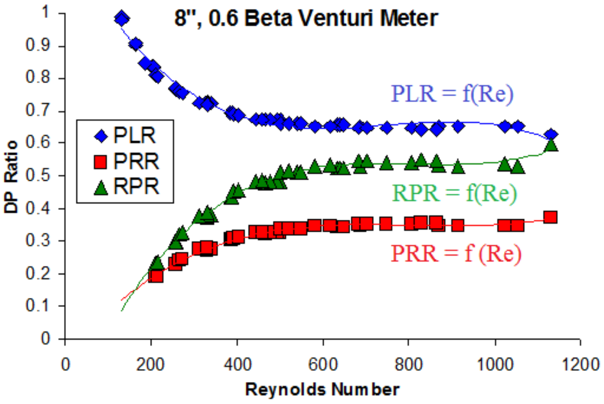

Fig 12. Venturi Meter DP Ratio vs. Re. No.

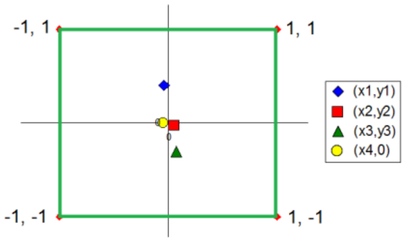

Fig 13. Venturi Meter Sample Point Calibration Prognosis Result.

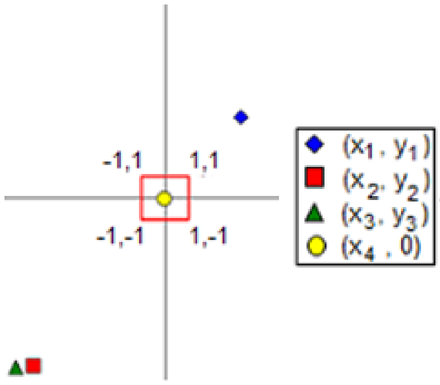

Fig 14. 8”, 0.6β Venturi Meter, 1st Guess of 0.5 Pa.

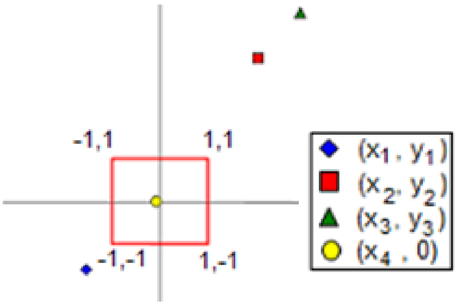

Fig 15. 8”, 0.6β Venturi Meter, 2nd Attempt of 1 Pa.

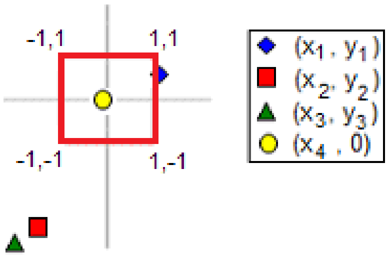

Fig 16. 8”, 0.6β Venturi Meter, 3rd Attempt of 0.75 Pa.

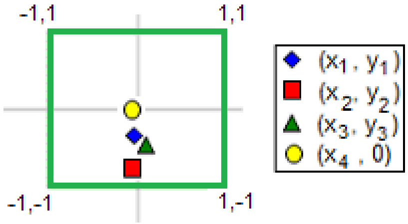

Fig 17. 8”, 0.6β Venturi Meter, 4th Attempt of 0.85 Pa.

Fig 13 shows the Prognosis result for a randomly selected calibration point. For a correctly operating Venturi meter with a known viscosity the diagnostic points fall inside the NDB. Figure 13 is from a calibration point where the mass flow was 35.5 kg/s, and the fluid viscosity (μ) of 0.87 Pa.s produced a Reynolds number of 255, and a discharge coefficient of 0.7806. However, in the field the operator may not know the viscosity. Say a viscosity of 0.5 Pa.s is erroneously assumed, then the discharge coefficient is estimated as 0.842 and the associated flow rate prediction is 38.34 kg/s, which is an error of +7.9%. Figure 14 shows the corresponding Prognosis response. Prognosis is indicating that the viscosity input is in error. The operator must iterate to find the correct viscosity. Try the higher viscosity of 1 Pa.s. Figure 15 shows that the diagnostic pattern has inverted indicating that the viscosity value was increased too much. Trying the mid viscosity of 0.75 Pa.s gives Figure 16. The points are getting closer to the NDB and the pattern has inverted back to indicating the viscosity input is now slightly too low. A further iteration to a viscosity of 0.85 Pa.s is shown in Figure 17. All points are now in the NDB. The estimated viscosity is 0.85 Pa.s. The associated estimates are a discharge coefficient of 0.7788, a Reynolds number of 262 and a mass flow rate of 35.46 kg/s, i.e. -0.23% difference from the reference meter's value. Prognosis has estimated the viscosity, thereby allowing the Reynolds number, discharge coefficient and mass flow rate to be correctly deduced when the operator did not know the viscosity from an external source.

5b Cone Meter

Figures 18 & 19 show CEESI 8", 0.75β cone meter (see Fig. 1) high viscosity data. Figure 18 shows three flow coefficients vs. Reynolds number calibration data.

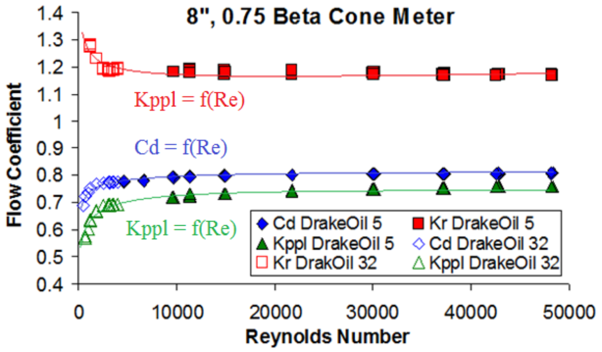

Fig 18. Cone Meter Flow Coefficients vs. Re. No.

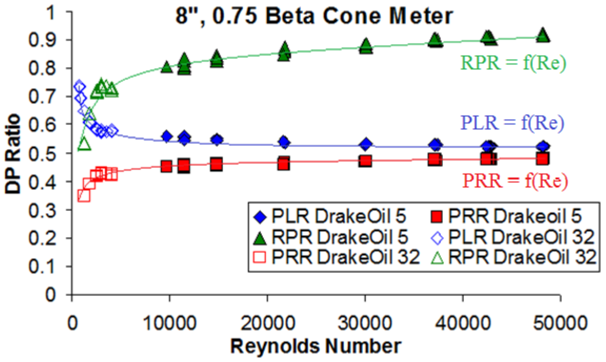

Fig 19. Cone Meter DP Ratio vs. Re. No.

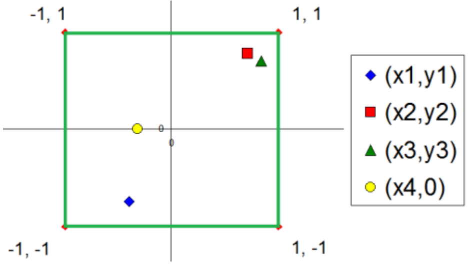

Fig 20. Cone Meter Sample Point Calibration Prognosis Result.

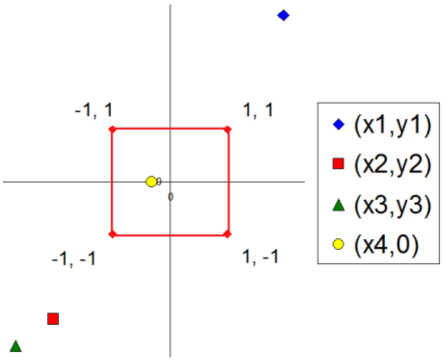

Fig 21. 8", 0.75β Cone Meter, 1st Guess of 0.01 Pa.

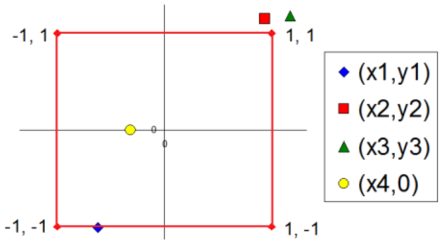

Fig 22. 8", 0.6β Venturi Meter, 2nd Guess of 0.2 Pa.s

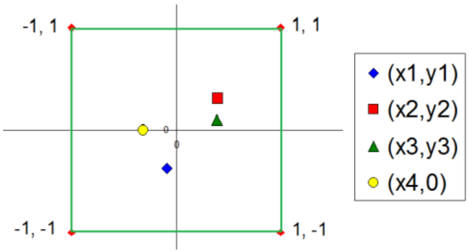

Fig 23. 8", 0.75β Cone Meter, 3rd Guess of 0.15 Pa.

Figure 19 shows three DP ratio vs. Reynolds number calibration data. This data was used to calibrate the meter calibrate the Prognosis system.

Fig 20 shows the Prognosis result for a randomly selected calibration point. For a correctly operating cone meter with a known viscosity the diagnostic points fall inside the NDB. Figure 20 is from a calibration point where the mass flow was 50.1 kg/s, and the fluid viscosity (μ) of 0.1783 Pa.s produced a Reynolds number of 1765, and a discharge coefficient of 0.7674.

However, in the field the operator may not know the viscosity. Say a viscosity of 0.01 Pa. is erroneously assumed, then the discharge coefficient is estimated as 0.8066 and the associated flow rate prediction is 52.66 kg/s, which is an error of +5.1%. Figure 21 shows the corresponding Prognosis response. Prognosis is indicating that the viscosity input is in error. The operator must iterate to find the correct viscosity. Try the higher viscosity of 0.2Pa.s. Figure 22 shows that the diagnostic pattern. The diagnostic points have converged towards the origin but have slightly overshot. A slight reduction in the viscosity prediction should take them closer to the origin, i.e. the correct result. Trying a viscosity input of 0.15 Pa.s gives Figure 23. The points are closer to the origin. This is as close as the method can practically get to predicting the true viscosity. The associated discharge coefficient is 0.7651, a Reynolds number of 2091 and a mass flow rate of 112.11 kg/s, i.e. -0.3% difference from the reference meter's value. Prognosis has estimated the viscosity, thereby allowing the Reynolds number, discharge coefficient and mass flow rate to be correctly deduced when the operator did not know the viscosity from an external source.

5c **Wedge Meter**

Figures 24 & 25 show CEESI 8", 0.707β wedge meter (see Fig. 1) high viscosity data. Figure 24 shows three flow coefficients vs. Reynolds number calibration data. Figure 25 shows three DP ratio vs. Reynolds number calibration data. This data was used to calibrate the meter calibrate the Prognosis system.

Fig 26 shows the Prognosis result for a randomly selected calibration point. For a correctly operating wedge meter with a known viscosity the diagnostic points fall inside the NDB. Figure 26 is from a calibration point where the mass flow was 129.2 kg/s, and the fluid viscosity (μ) of 0.1755 Pa.s produced a Reynolds number of 4839, and a discharge coefficient of 0.7002.

However, in the field the operator may not know the viscosity. Say a viscosity of 1 Pa. is erroneously assumed, then the discharge coefficient is estimated as 0.7351 and the associated flow rate prediction is 135.7 kg/s, which is an error of +5%. However, the viscosity input is wrong, and the other diagnostic parameters therefore notice something is not correct (see Figure 27). Prognosis is indicating that the viscosity input is in error. The operator must iterate to find the correct viscosity.

Trying a higher viscosity of 2 Pa.s. gives Figure 28. The diagnostic points have diverged away from the origin indicating that the viscosity was lower than 1 Pa.s, not higher. Trying a viscosity input ten times less than the original guess gives Figure 29. The diagnostic points have now over shot the NDB, i.e. the fluid viscosity is higher than 0.1 Pa.s. Trying 0.15 Pa.s gives Figure 30. The diagnostic points are now inside the NDB, but they can be brought closer to the origin. A further iteration to

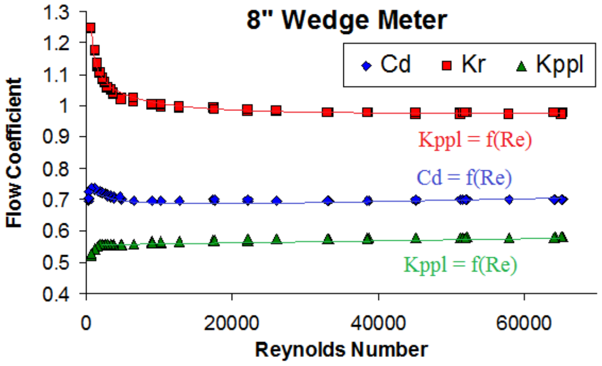

Fig 24. Wedge Meter Flow Coefficients vs. Re. No.

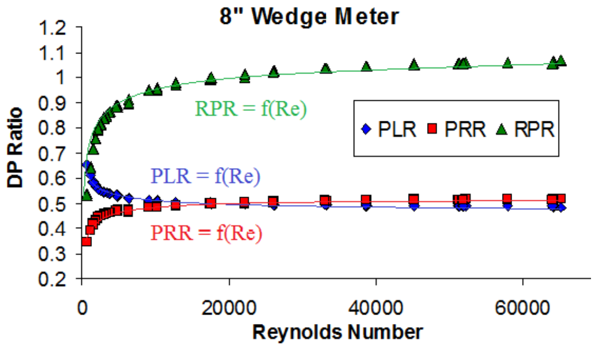

Fig 25. Wedge Meter DP Ratio vs. Re. No.

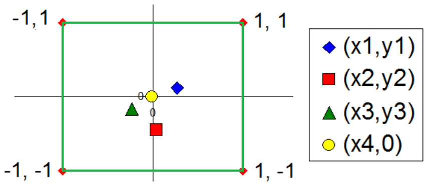

Fig 26. Wedge Meter Sample Point Calibration Prognosis Result.

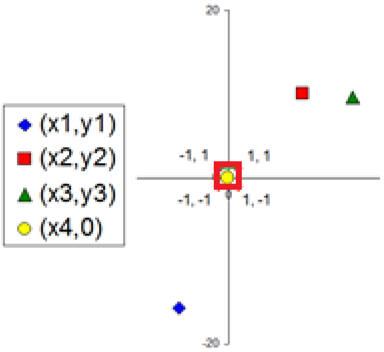

Fig 27. 8", 0.707β Wedge Meter, 1st Guess 1 Pa.s.

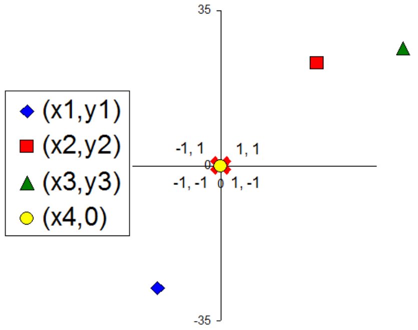

Fig 28. 8", 0.707β Wedge Meter, 2nd Guess 2 Pa.s.

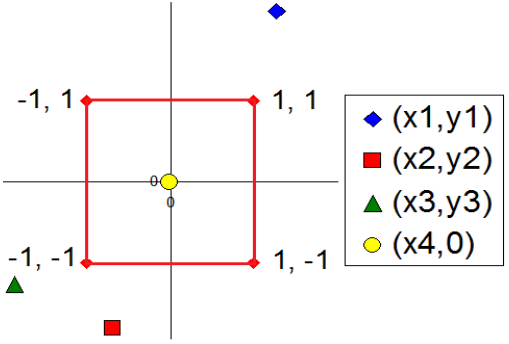

Fig 29. 8", 0.707β Wedge Meter, 3rd Guess 0.1 Pa.s.

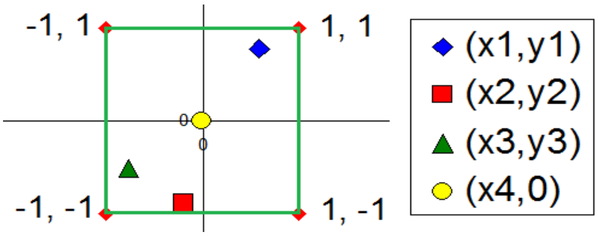

Fig 30. 8”, 0.707β Wedge Meter, 5th Guess 0.15 Pa.s.

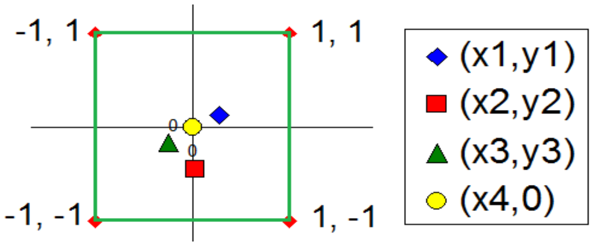

Fig 31. 8”, 0.707β Wedge Meter, 5th Guess 0.175 Pa.s.

a viscosity of 0.175 Pa.s is shown in Figure 31. This is as close as the method can practically get to predicting the true viscosity. The associated discharge coefficient is 0.7012, a Reynolds number of 4860 and a mass flow rate of 129.4 kg/s, i.e. +0.14% difference from the reference meter’s value. Prognosis has estimated the viscosity, thereby allowing the Reynolds number, discharge coefficient and mass flow rate to be correctly deduced when the operator did not know the viscosity from an external source.

7. Conclusion

Highly viscous fluid flow can be a challenge to flow meter. Whereas DP meters tend to have approximately constant discharge coefficients over large Reynolds number ranges, they can have highly variable discharge coefficients at very a low Reynolds number range.

In order to get a low flow rate uncertainty from a DP meter it is necessary to calibrate the meters discharge coefficient vs. Reynolds number relationship. It is important to calibrate the DP meters across the Reynolds number range and not just the flow rate range.
Calibrating a DP meter across a flow rate range using a different fluid than the application (e.g. water flow for an oil flow application) can lead to the calibration being across a different Reynolds number range than the meter’s application. This can cause a metering error. It is important to calibrate a flow meter across the applications Reynolds number range.

Wedge meters are often promoted as DP meters that maintain a constant discharge coefficient at low Reynolds numbers. This was found to be only partially true. The wedge meter tested was more resistant to the effect Reynolds number has on the discharge coefficient than other DP meters tested, but it was not immune. At very low Reynolds numbers (< 5,000) the discharge coefficient vs. Reynolds number relationship of the meter tested became non-linear. The wedge meter discharge coefficient variation with Reynolds number was less than that found with the available Venturi and cone meter data sets, but it was still significant. For low Reynolds number applications wedge meters, like all DP meters, should be calibrated across the applications Reynolds number range.

Once calibrated, in the field the operator presently has to supply the heavy oil fluid viscosity from a trusted external source as an operator input. However, this can be difficult information to get in the field. Without low uncertainty predictions of the highly viscous oil flow viscosity the corresponding flow rate prediction can have gross biases, even when the DP meter is calibrated across the appropriate Reynolds number range. DP Diagnostics have now shown with CEESI (for wedge & cone meters) and with NEL (for Venturi meters) that a diagnostic (‘Prognosis’) system ready DP meter can estimate the fluid viscosity thereby supplying the unknown parameter in order to meter the flow.

8. References

[1] Rabone J., et al “Prognosis Applied to High Viscosity Flows”, SE Asia Flow measurement Conference, Kuala Lumpur, Malaysia, March 2014

[2] Rabone J. et al “DP Meter Diagnostic Systems – Operator Experience”, North Sea Flow Measurement Workshop 2014, St Andrews, UK.