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## Technical Paper

# A Differential Pressure Meter for Low Reynolds Number Applications

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## 1 INTRODUCTION

Heavy oils are characterised depending on their density rather than their viscosity [1]. Although there are various definitions for what constitutes heavy oil it is commonly agreed that the majority contain impurities such as asphaltenes, waxes and carbon residue. The API gravity definition, a common definition used in the oil and gas industry worldwide, states that heavy oil has an upper limit of 22°. Figure 1 shows the upper and lower limits of various categories of oil as stated in the API gravity definition.

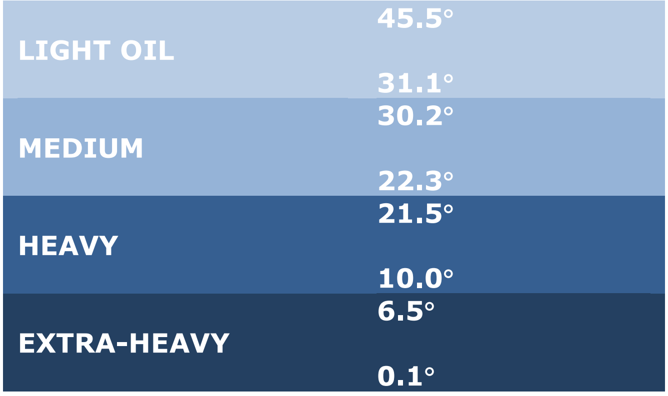

**Figure 1: Classifications of Oil**

Confirmed world oil reserves are split approximately into 70% high viscosity and 30% (low viscosity) conventional light oils. High viscosity oils are regarded as a vital energy resource for the foreseeable future, with significant yields forecast at 100 years or more.

A literature review conducted by NEL and Oxford University highlighted the issues facing application of conventional flow meters to high viscosity fluids [2]. Following on from the review, an initial experimental test programme [3] was instigated using a selection of conventional flow meters applied in viscous fluids. The overall conclusion from this work reinforced the notion that liquid flow meters cannot simply be relocated from low to high viscosity service without suitable characterisation or modification, nor can calibrations conducted in a low viscosity medium necessarily be applied to heavier crudes without appropriate compensation.

Flow measurement of high viscosity fluids is difficult for most metering technologies. At Reynolds numbers between 2,000 and 5,000 the flow enters the transitional region where the flow profile changes rapidly and randomly. Lower than 2,000, the flow enters the laminar region, which is characterised by a parabolic velocity profile. Both flow regions have significant problems associated with them and in general, flow measurement uncertainty is larger than in turbulent flow.

Heavy oil presents numerous challenges to accurate flow measurement. One challenge is the increased susceptibility of viscous liquids to entrain gas. Different metering devices will most likely be affected by gas entrainment in different ways and to varying degrees, but to date the most appropriate technologies for viscous flow measurement have not been defined.

Differential pressure meters play a major role in conventional oil and gas production. However it is widely known that they do not perform as well in high viscosity fluids owing to the increase in frictional forces within the meter [4-7]. This increase results in an increased sensitivity of the discharge coefficient to Reynolds number. Therefore, if the Reynolds number is not accurately known, then significant errors can be found in the overall flow measurement using the differential pressure meter. From ISO 5167-2 [8], a Reynolds number of 5,000 is the lowest applicable limit for a standard orifice plate.

There are some differential pressure meters that are used in low Reynolds numbers and are thought to be applicable through their linear discharge coefficient. These are quadrant edge orifice plates, conical entrance orifice plates and wedge meters. The use of quadrant edge and conical entrance orifice plates are detailed in ISO 15377:2007 [9]. However, there is a minimum and maximum Reynolds number even for these primary elements that limit their applicability.

In conventional oil and gas applications, the differential pressure meter is by far the most popular technology in terms of the number of units sold. There are a number of advantages that have facilitated this market share including cost, ease of use and calibration and maintenance requirements. In contrast, there is little evidence of a large commercial uptake of differential pressure meters for low Reynolds number applications (see Section 2). This is primarily due to their poor performance caused by a non-linear discharge coefficient in low Reynolds numbers.

This paper shows a review of the current market for heavy oil flow measurement and highlights a surprising technology gap for a cost-effective general process measurement device that differential pressure technology typical fills in conventional applications. A new method is presented that can eliminate the Reynolds number effect within differential pressure meters (and other intrusive devices) allowing for an improved performance in low Reynolds number applications. The results of test work on a number of Venturis is presented with detailed look at an 8 inch quadrant edge orifice plate. Errors in flow, Reynolds number, density and viscosity are shown.

## 2 MARKET STUDY

### 2.1 Flow Measurement Requirements in Heavy Oil

In the oil and gas industry there are various stages from production to refined product that require measurements to be made for a variety of different reasons. Typically, the stages are called upstream, midstream and downstream and are shown in Figure 2.

In the upstream industry heavy oil is produced both onshore and offshore in one of two ways depending greatly on the fluid viscosity and the reservoir depth. If the reservoir is shallow it can be dug directly out of the ground similar to surface mining. For deeper reservoirs, conventional well to riser pipe production is used. If the fluid is classed as 'conventional' heavy oil (300 cP – 2000 cP), then conventional production techniques are used with some enhanced oil recovery (EOR) techniques. However, for 'Extra Heavy Oil' (up to millions cP), typically called oil sands or tar sands, the hydrocarbon is almost solid in situ and EOR methods such as SAGD or CHOPS must be used. In recent years, more research has been aimed at improving production in these applications using different EOR techniques.

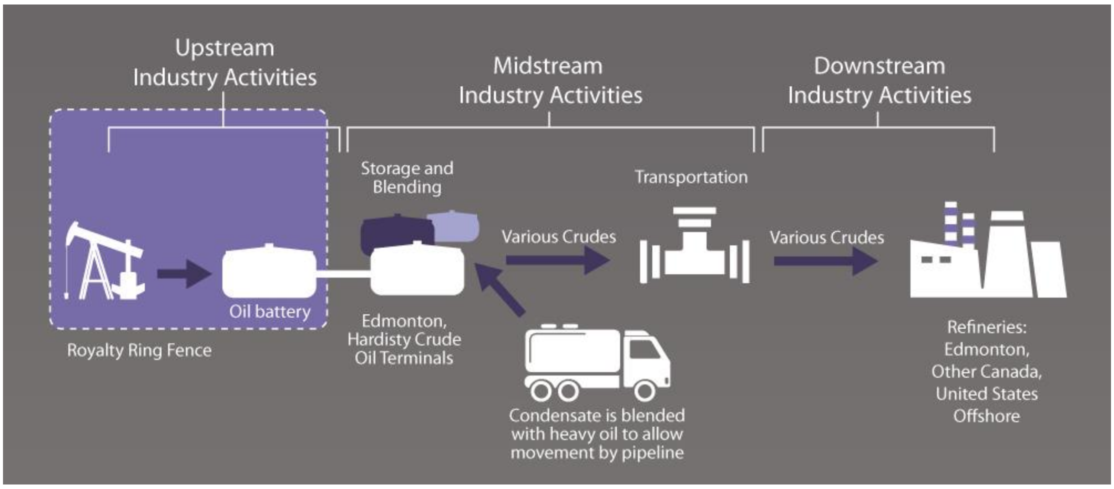

**Figure 2: Stages in heavy oil production**

In both cases, once produced, the task is to get the oil into a suitable state for transport. If it is mobile and clean enough this can be done immediately (entering the midstream stage) although this is not common. Usually, the heavy oil is stored in tankers on site allowing for solids and water (BSW) to separate due to gravity. The oil is usually mixed with a diluent upon removal from this tank to ensure the oil meets the criteria for transport. The criteria is typically based on a minimum viscosity of the fluid at a given temperature and dictated by the pipeline operator. Transport is either by truck to refinery, truck to pipeline or direct into pipeline.

In terms of measurements required, production will typically include allocation measurement and general process measurements e.g. outlets from separators or run down to storage tanks. These measurements are typically not directly related to the sale of goods for custody transfer or fiscal applications although they may be used in the calculation of these values. The uncertainty required for these measurements will be no better than 1% (all uncertainties stated are at 95% confidence).

When fluids are passed to the midstream stage for transport there may be a requirement for more accurate measurements to the level of custody transfer (0.25%). The most important measurement at this stage is probably the viscosity of the fluid, which is required to meet a certain minimum level for a reference temperature (variable in Canada). As mentioned, to achieve the target viscosity, the heavy oil is mixed with lighter oil called a diluent.

Diluent is a costly resource and there is a need to minimize its use. The current method of determining how much diluent to use is to take samples of the mixed fluid and run laboratory analysis. This can take a couple of hours to obtain results meaning the there is a chance of using either too much or not enough diluent. Both cases can result in financial loss. A real time measurement of mixed fluid viscosity is available by using inline viscometers. However, these are quite costly and are very dependent on process conditions. The typical uncertainty in the inline viscometers is typically in the region of ± 5%.

Many EOR techniques are now employing expensive polymer chemicals for better recovery. These polymers can be viscous in nature and have non-Newtonian properties. Many operations dilute the polymer with water to attain a target compound. However, the mixture properties are not measured in real-time and often assumed to mix well as per laboratory trials and yields.

For optimising the EOR methods there is a requirement to know what fluid and properties are entering the well to determine how well the recovery has been enhanced and whether the correct mixture has been formed.

For midstream applications, the task is to get the oil from the production site to the refinery. This may be a few hundred or a few thousand kilometers. For example, some pipelines in the Alberta province in Canada stretch from Fort McMurray across the US/Canadian border and all the way to refineries in Texas and Louisiana.

For these applications the main requirements for measurement are verification of fluid quantity and quality entering the system for allocation and flow assurance. This is completed using inline flow meters and sampling systems. The measurement issues described above are still present.

The other main measurement application during the midstream stage is for leak detection. Many pipeline operators are merited on their loss figures. Typically, this is measured using a large number of full bore USM to limit the pressure loss in the system. However, these are known to exhibit some measurement issues when operated in non-ideal conditions such as gas flashing.

Using the loss detection meters as an array of meters along the pipeline will deliver a number of measured flow rates with associated uncertainties in these measurements. When no leaks are present, the measured flow rates should agree within the given uncertainties of each meter. If this is not the case, then it indicates that there is a potential leak in the system. There are other potential causes of this deviation but it does indicate the need for investigation.

For leak detection, the lowest uncertainty in measurement is desired, as this will provide the best resolution in the detection of leaks in the system. Increasing the uncertainty will result in potential leaks not being noticed owing to the larger random errors that can be statistically attributed to the measurement themselves.

Lastly, there is a need for custody transfer level measurements being made at the end of the pipeline. This is typically achieved using positive displacement meters with onsite prover. This is a very costly system but is accurate, repeatable and reproducible. It is also the basis of how much each party gets paid for their product fed into the pipeline and as such has the larger focus in terms of continued maintenance and effort. A system like this is the best choice for the application.

For downstream applications, the task is to refine, store and transport refine petrochemicals for end use. The crude is processed in refineries that separate lighter hydrocarbons from the heavier ones (typically shorter chained or smaller molecules are classed as lighter). There are several measurement applications here but the majority fall into general process measurement for safety, control and optimisation of process equipment.

Refineries are larger than production sites and have many more measurement sites. The fluids tend to be cleaner and systems have more space and less weight constraints attached to them.

The fluids vary in physical properties and some elements tend to be more viscous than the original fluid transported in the midstream application. The lighter components are typically made into petrol, diesel and other fuels. Other components are used as feedstock for the chemical or polymer industry and lastly the heavier components are often classed as waste but find some application in bitumen and asphalt for roads, viscous fuels for shipping (often called bunkering fuels) and other low value solutions.

In recent years, there has been a push for upgrading the heavier components to make them more valuable. The upgrading typically uses energy to break carbon chains hence making the overall products lighter and similar to more commonly used fuels. The upgrading also reduces the sulphur content of the oil improving its value again.

In terms of measurements, this upgrading offers more opportunities for general process measurements as described above. Once all processing is completed it is likely the refined products will be transported for sale or for further value added processes. This transport may be by pipeline or by truck or rail. Again, a custody transfer or fiscal measurement may be completed at this point.

## 2.2 Economics

Heavy oil and bitumen form a crucial part of the world's hydrocarbon-based energy supply with 70% of the remaining discovered reserves falling into this category. The production of this natural resource is more costly than conventional oils and as such needs a higher oil price to attain commercial viability.  As such, the price of oil is a critical factor in heavy oil production projects. However, armed with this knowledge, there is a great deal of work currently focused on reducing the operational costs of extracting heavy oils and bitumen.

The US Geological Survey shows close to 8 trillion barrels of heavy oil and natural bitumen discovered worldwide with an additional trillion in prospective discoveries still to come. In North America alone there is close to a third of this value and where the greatest commercial production is taking place.

In Canada, of the 1.7 trillion barrels of oil in place, only 170 billion barrels are currently classed as economically recoverable (10%). As of 2015, close to 25 billion barrels are part of and are under active development in Canada. Currently, 3 million barrels/day are produced from oil sands with the Canadian Association of Petroleum Producers (CAPP) expecting a 50% increase to 4.8 barrels/day by 2030 suggesting a rapidly growing market – with the caveat as described above linked to the oil price.

In terms of application numbers in this market, to attain 3 million barrels/day the number of production sites is around 23,000 batteries. Typically, each battery has between 5 and 10 wells producing resulting in over 100,000 producing wells. For upstream applications, a substantial number of these wells will require allocation measurement systems as well as storage and export measurements. In addition, for transport purposes, many applications will require dilution to meet pipeline entry requirements using expensive diluent.

For transport, one of the largest pipeline companies in Canada is Enbridge. They operate over 10,000 miles in North America transporting heavy oil, conventional oil and natural gas to refineries and other processing plants. Lines 1, 3 and 4 connect Edmonton terminal in Albert to Superior in Wisconsin, USA through 1098 mile pipelines that has between 500 and 800 flow meters in total used for the sole purpose of leak detection.

At the refinery, there can be a wide number of applications from process control, safety and general process measurements that require knowledge of the flow rate within a pipe or the physical properties of the fluid. The number depends on the size of the plant but from enquiry information from manufacturers they are asked for hundreds if not thousands of orifice plates at a time suggesting very large requirement in these facilities. Alberta alone has 9 refineries with another 4 in other parts of Canada. The USA hosts 137 operating refineries (2015).

Looking further afield shows production of heavier crudes in South America (Venezuela and Brazil) and the Middle East (nearly all) in particular with other regions known to have plans for exploitation in the future. Currently, Canada has around a fifth of the heavy oil supply available in the world and is probably exploiting these reserves to a much higher degree than other countries.

It is important to stress that for every barrel of oil produced in this environment it is not measured once only. It is measured constantly throughout the production, transportation and refinement process which could be in the region of 10-20 times dependent on distance to travel, allocation set up and partners involved.

Considering all of the above it is thought that there are currently over 1,000,000 applications worldwide in the oil and gas industry.

In current conventional applications, differential pressure flow meters achieve a 40% market share of world's flow meters sales in terms of meter numbers. Around 60% of this figure is made up of standard orifice plates. This meter type is by far the most common technology on the market and it has achieved this status by offering many advantages to end-users. Primarily, they are low cost, easy to understand and operate, have a lot of history, easy to maintain and have prescriptive standards (ISO 5167: parts 1-6). In addition, standard orifice plates do not need to be calibrated as long as they conform to the geometry's in the standard. All in all they are cost effective and reliable.

In high viscosity applications, their use is very limited and they achieve a market share in the region of 1%. This has been primarily due to their poor performance in these applications. Some of the largest manufacturers of orifice plates in the world have annual sales in the region of 10,000 units. The number of quadrant edge orifice plates sold per annum is typically between 2 and 4% of the total figure (information from multiple companies). The number has been seen to grow in the past decade as well. Globally, it is estimated that 500-1,000 quadrant edge orifice plates are sold per annum.

NEL test data from 2005 onwards were analysed to see which meters are most common for low Reynolds applications (Table 1). Only tests where the maximum test Reynolds number was < 8000 were considered. This was to highlight tests where low Reynolds flows were predominant.

**TABLE 1**

**Low Reynolds number tests at NEL since 2005**

| | | |
|---|---|---|
| Coriolis | 937 | 49.5% |
| Ultrasonic | 698 | 36.9% |
| Positive Displacement | 168 | 8.9% |
| Turbine | 44 | 2.3% |
| Venturi | 0 | 0.0% |
| Orifice Plate (standard, quadrant edge and conical entrance tested) | 23 | 1.2% |
| Wedge | 22 | 1.2% |
| Cone | 0 | 0.0% |
| Total | 1892 | |

Table 1 shows that the majority of meters tested for low Reynolds number flows are Coriolis meters and ultrasonic meters. This agrees with literature which suggests that most custody transfer flow meters for high viscosity fluids fall into one of four categories: positive displacement, Coriolis, helical turbine and ultrasonic [11]. Table 1 does not tell the whole story however as it is likely that any positive displacement or turbine meters would have an in situ proving capability and hence would not require a laboratory calibration. For differential pressure meters there is very little interest from industry in laboratory testing. Likely reasons are poor performance and the use of quadrant edge and conical entrance orifice plates with [9].

## 2.3 Summary

It is clear that differential pressure meters are not as prevalent in low Reynolds number applications as they are in conventional ones. The difference in market uptake is primarily down to perceived performance of these devices in low Reynolds numbers. However, there are many applications, with heavy oil production in particular, that will require general process measurements in low Reynolds numbers with uncertainties in the region of 2% or better.

There are a number of measurement challenges in low Reynolds numbers and the majority of meters can exhibit a decreased performance. If improvements can be made to differential pressure meters to reduce the effect of some of these measurement challenges, they would be an ideal candidate to meet the general process measurement uncertainty target.

One of the primary advantages of these meters is cost. In the current economic climate, cost is king, and the ability to meet an end-user specification at a reduced cost is paramount. In addition, having instrumentation do more limits the ongoing staff time and effort to maintain equipment. For instance, measuring flow, density and viscosity in the one unit offers a number of advantages.

In summary, an improvement in performance of differential pressure meters in low Reynolds number can help them achieve a market share similar to conventional applications.

## 3 THEORY

### 3.1 Nomenclature

| **Symbol** | **Name** | **Symbol** | **Name** |
|---|---|---|---|
| $P$ | Static Pressure | $z$ | Elevation |
| $\rho$ | density | $Q_v$ | Volume flow rate |
| $g$ | Gravitational constant | $C_d$ | Discharge coefficient |
| $u$ | Velocity | $\varepsilon$ | Absolute roughness |
| $d$ | Throat diameter | $C_g$ | Coefficient of geometry |
| $D$ | Pipe diameter | $Re$ | Reynolds number |
| $\beta$ | Ratio of throat to pipe diameter | $\mu$ | Dynamic Viscosity |
| $\lambda$ | Darcy-Weisbach friction factor | $\Delta P_4$ | Pressure differential across straight pipe |
| $\Delta P_1$ | Pressure differential across restriction | | |

| **Subscripts** | | **Subscripts** | |
|---|---|---|---|
| *1* | At location 1 | *D* | In pipe |
| *2* | At location 2 | *d* | In throat |

### 3.2 New Method

Consider a typical discharge coefficient versus Reynolds number curve for a Venturi meter [4] as shown in Figure 3. Below a Reynolds number of 50,000, the discharge coefficient becomes increasingly non-linear with decreasing Reynolds number. Around the transition region, a hydraulic hump can be seen with an increase in discharge coefficient before it begins to fall off sharply again with decreasing Reynolds number into laminar flow.

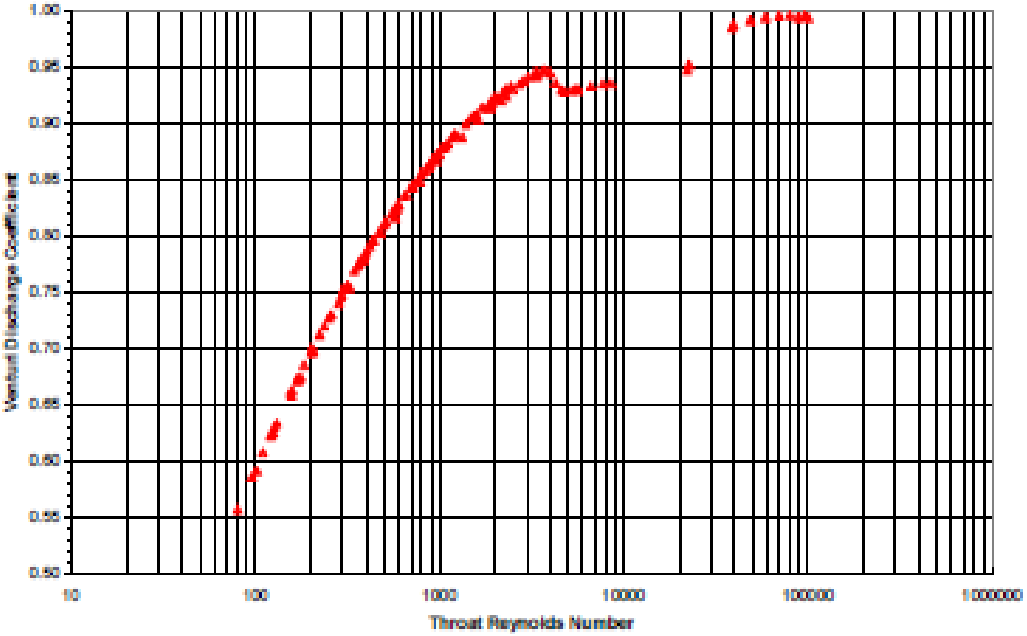

**Figure 3: Typical discharge coefficient versus Reynolds number relationship**

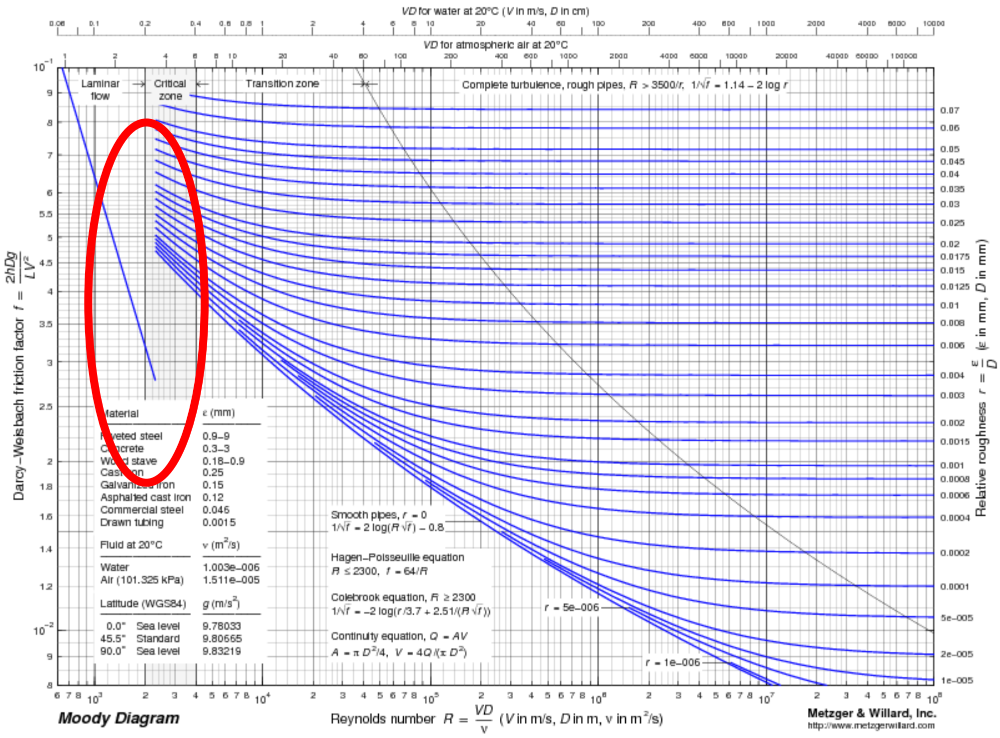

**Figure 4: Darcy-Weisbach friction factor versus Reynolds number**

This behaviour is typical in nearly all differential pressure meter types and can be seen in literature [4-7]. The shape is replicated in the very well used and well known Moody plot which relates pipe friction factor to Reynolds number shown in Figure 4. Note the characteristic change in friction factor in turbulent to laminar flow in the critical zone highlighted in red.

The similarities suggest a link between friction factor and discharge coefficient which matches with theory as will be shown through equations 1 – 11.

Consider equations 1 and 2, which show the Bernoulli equation and the differential pressure flow equations respectively. Bernoulli assumes inviscid flow i.e. a fluid with zero viscosity and links the dynamic, static and potential energies within the system. Equation 2 is derived from Bernoulli for an incompressible fluid and includes the discharge coefficient to account for differences from theory i.e. a real fluid with non-zero viscosity (amongst other differences).

$$\frac{p_1}{\rho g}+\frac{u_1^2}{2g}+z_1=\frac{p_2}{\rho g}+\frac{u_2^2}{2g}+z_2 \tag{1}$$

$$Q_v = C_d\cdot\frac{\pi\cdot d^2}{4}\cdot\frac{1}{\sqrt{\left(1-\beta^4\right)}}\cdot\sqrt{\frac{2\cdot(P_1-P_2)}{\rho}} \tag{2}$$

Higher fluid viscosity increases the pressure drop through the meter and therefore increases the measured differential pressure. Or said another way, the higher the fluid viscosity, the less the measured pressure drop fully represents the change in static/dynamic energies through a restriction as predicted by Bernoulli.

It follows then, that as Reynolds number decreases (typically as viscosity increases) that the discharge coefficient should decrease to account for the added pressure drop caused by viscous friction. Friction factor plays an important role in this calculation and therefore it is clear that there is a relationship to discharge coefficient. Friction factor can be calculated through the Darcy-Weisbach equation, equation 3.

$$\lambda = \frac{2\Delta P_4 \cdot D}{\rho \cdot L \cdot {u_D}^2} \tag{3}$$

It is applicable across all Reynolds numbers and indications of friction factor values with respect to Reynolds number can be found in the Moody Plot (Figure 4). It’s important to point out that in laminar flow the friction factor is independent of pipe roughness but this is not the case in turbulent flow.

Friction factor is dependent on system geometry, the fluid velocity and fluid density with the primary measurement being the pressure drop along a straight length of pipe. The calculation of flow rate through a restriction and friction factor both require a measurement of differential pressure as the primary measurement point. Consider the following meter set up as shown in Figure 5.

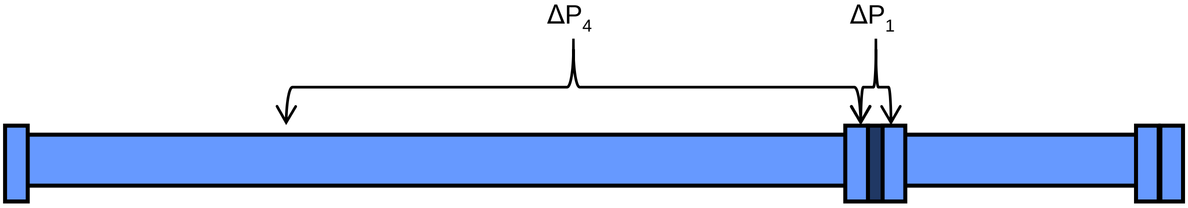

**Figure 5: Orifice plate installed in a typical metering run (flow from left to right)**

From (3), friction factor is dependent on pipe velocity squared. Rearrange (2) in terms of pipe velocity gives (4) and squaring (4) results in (5).

$$u_D = C_d \cdot \beta^2 \cdot \frac{1}{\sqrt{(1-\beta^4)}} \cdot \sqrt{\frac{2 \cdot (\Delta P_1)}{\rho}} \tag{4}$$

$${u_D}^2 = \frac{2 \cdot {C_d}^2 \cdot \beta^4 \cdot \Delta P_1}{\rho(1-\beta^4)} \tag{5}$$

Inserting (5) into (3) and rearranging yields a new equation for friction factor that is independent of physical properties (6).

$$\lambda = \frac{\Delta P_4}{\Delta P_1} \cdot \frac{C_g}{{C_d}^2} \tag{6}$$

where
$$C_g = \frac{D\left(1-\beta^4\right)}{L \cdot \beta^4} \tag{7}$$

The relationship between friction factor and Reynolds number is well known for both laminar (8) and turbulent flows (9 – Colebrook-White). Once friction factor is calculated so too can Reynolds number be obtained.

$$\mathrm{Re} = \frac{64}{\lambda} \tag{8}$$

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{\varepsilon}{3.7D} + \frac{2.51}{\mathrm{Re}\sqrt{\lambda}}\right) \tag{9}$$

From calibration, standard equations or other, the relationship between discharge coefficient and pipe Reynolds number can be obtained and the appropriate discharge coefficient can be applied.

The new method can be taken further still by including another measurement technique. Figure 6 provides the example of the set up using a clamp-on ultrasonic meter in the straight length of pipe upstream of the meter. Other technologies can be used in a similar method.

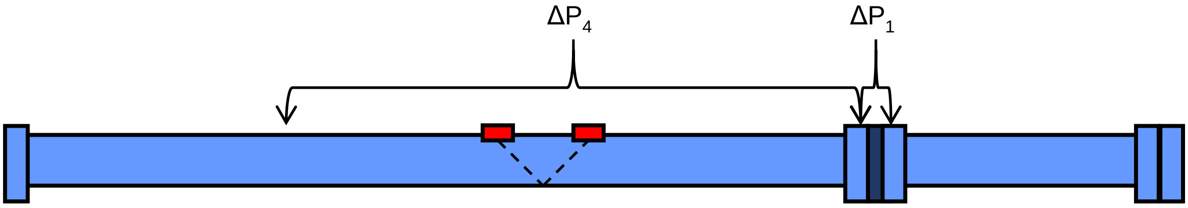

**Figure 6: Orifice plate with additional clamp-on ultrasonic measurement upstream of primary element**

Rearranging (3) in terms of density provides (10).

$$\rho = \frac{2\Delta P_4 \cdot D}{\lambda \cdot L \cdot {u_D}^2} \tag{10}$$

The calculated density from (10) can then be used in (2) for calculation of volume flow rate (or alternatively rearranged for mass flow rate) with previous calculation of the correct discharge coefficient.

In addition, with knowledge of density, velocity and Reynolds number it is possible to calculate viscosity of the fluid through (11).

$$\mu = \frac{\rho \cdot u_D \cdot D}{\mathrm{Re}} \tag{11}$$

During calibration, correction factors can be obtained and then applied in operation as per standard practice. The result of the above theory provides a solution to Reynolds number effects on intrusive flow measurement devices. Specifically, any technology, not just differential pressure, that causes a measurable, repeatable and reproducible pressure drop can use this method to calculate Reynolds number in real-time.

Furthermore, by incorporating an additional measurement it is possible to derive the physical properties of the flowing fluid in real-time.

### 3.2 Use of Quadrant Edge Orifice Plates

For quadrant edge orifice plates the minimum and maximum Reynolds numbers for a specific beta can be calculated using equations 12 and 13 respectively (both found in [9] and [10]).

$$\mathrm{Re}_{\min} = 1000\beta + 9.4\times10^{6}(\beta - 0.24)^{8} \tag{12}$$

$$\mathrm{Re}_{\max} \le 10^{5}\beta \tag{13}$$

Table 2 shows these values and expected discharge coefficients ($C_d$) for a range of betas.

**TABLE 2**

**Minimum Re and $C_d$ Values for Quadrant Edge Orifice Plates for Various β**

| β | $\mathrm{Re}_{\min\ (pipe)}$ | $\mathrm{Re}_{\max\ (pipe)}$ | $C_d$ |
|---|---|---|---|
| 0.245 (minimum allowed) | 245 | 24,500 | 0.772 |
| 0.3 | 300 | 30,000 | 0.774 |
| 0.4 | 404 | 40,000 | 0.781 |
| 0.45 | 485 | 45,000 | 0.789 |
| 0.5 | 696 | 50,000 | 0.802 |
| 0.6 (maximum allowed) | 3,252 | 60,000 | 0.844 |

The discharge coefficient can be calculated from equation 14 and is a function of beta. The uncertainty in this equation is 2% for β > 0.316 and 2.5 % when β ≤ 0.316.

$$C_d = 0.73823 + 0.3309\beta - 1.1615\beta^2 + 1.5084\beta^3 \tag{14}$$

# 4 TESTING

## 4.1 NEL Test Facilities

The UK National Standards Oil Flow Facility, located at NEL in East Kilbride, Scotland, consists of two separate flow circuits (A and B), each with a high capacity and a low capacity flow line. These can accommodate nominal pipe sizes from 0.5” to 8”, and can operate at line pressures up to 10 bar Test fluids can be delivered at flow rates up to 720 $m^3$/hr.

Figure 7 provides a schematic diagram of one of the flow circuits. The oil for each circuit is drawn from a 30 $m^3$ supply tank into the suction stream of the main pumps, from where it is discharged to the test lines. A conditioning circuit, linked to each tank, maintains the oil temperature to within ± 1 ºC of a pre-selected value (itself set in the range 5 – 60 ºC). Each test line can accommodate up to 30 m of horizontal straight length or alternative configurations as required. At the outlet of each test section, a manifold directs the fluid back to the storage tank or to one of the calibrated weigh tanks. Line temperature and pressure are monitored both upstream and downstream of the test section.

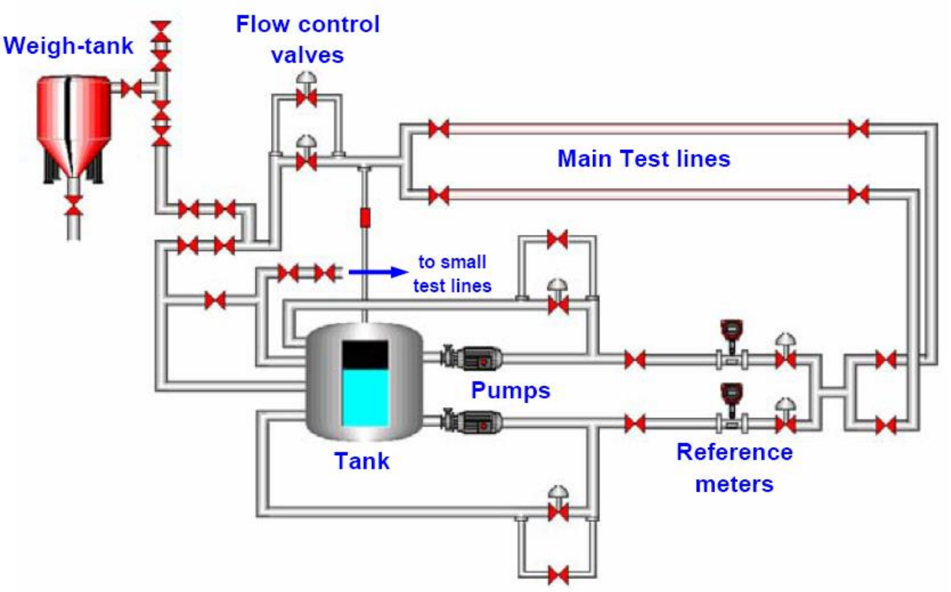

**Figure 7: Schematic Diagram of the NEL Oil Flow Test Facility**

The flow lines share a common primary standard weighbridge system consisting of four separate weightanks of 150, 600, 1500 and 6000 kg capacity. The facility is fully traceable to National Standards and is accredited by the United Kingdom Accreditation Service (UKAS).

For ‘primary’ calibrations, a gravimetric ‘standing-start-and-finish’ method is used to determine the quantity of fluid (volume or mass) that has passed through the flow meter under test and into the selected weightank.

The gravimetric weightanks constitute the primary reference standard of the NEL oil flow facility. Using the above technique, the overall uncertainty in the reference flow rate, expressed at the 95% confidence level is ± 0.03 % (k = 2).

For a ‘secondary’ calibration, the quantity of oil passing through the test meter is measured using a pre-calibrated reference meter, installed in series. The reference meters used at NEL have a history of previous calibrations and uncertainties of the order of ± 0.08 % (k = 2).

NEL has the following refined oils available as test fluids:

| | |
|---|---|
| ▪ Kerosene | (797 kg/m$^3$) |
| ▪ Gasoil | (826 kg/m$^3$) |
| ▪ Velocite | (843 kg/m$^3$) |
| ▪ Siptech | (862 kg/m$^3$) |
| ▪ Aztec | (870 kg/m$^3$) |

Measured densities for these fluids (at 20 ºC) are shown in brackets, while their typical viscosity behaviour as a function of temperature is plotted in Figure 8. As it is recognised that both the density and the viscosity of these test fluids can suffer small but finite changes over time – as a result of the cross-contamination of liquids within the flow circuits – these quantities are therefore re-measured offline on a periodic basis.

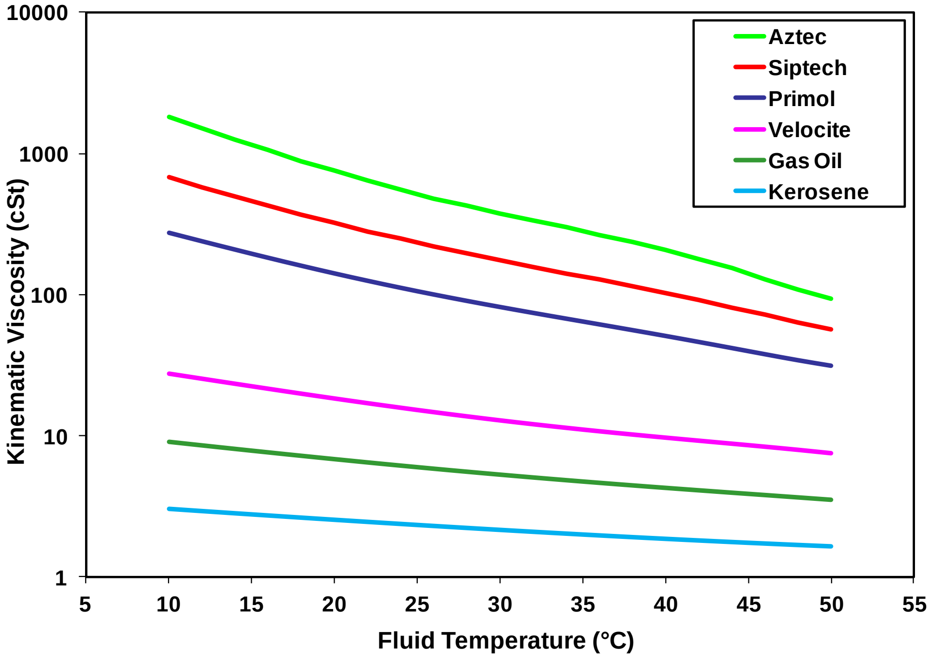

**Figure 8: NEL Test Fluids**

The offline density measurement for each oil type involves precision measurement with an Anton Paar DMA 5000 densitometer, which employs a vibrational technique. It accurately measures the oscillation period of a U-tube filled with fluid, and a best-fit curve is produced relating the oil density to temperature. This arrangement achieves an expanded uncertainty of 0.0088% at the 95% confidence level for measurements in the oil bath and of 0.0211% in the subsequent estimation of oil density in the test lines.

The dynamic viscosity of each test oil is also measured periodically offline, using an Anton Paar viscometer. The claimed uncertainty of this instrument is of the order of 0.5% at the 95% confidence level. The kinematic viscosity of the test fluid at a given line temperature is calculated from its dynamic viscosity and its density. The uncertainty in the calculated viscosity in the line is estimated to be ± 2%.

### 4.2 Test Method

Several differential pressure meters were tested with the new method with successful results. Table 3 shows a summary of the meter's geometries and Reynolds numbers tested.

In order to attain the Reynolds number range achieved in Table 3, each meter was tested at three temperatures spanning the range of 12 °C up to 40 °C which resulted in a range of viscosities. The test fluid was Aztec.

**TABLE 3**

**Summary of Test Meters and Reynolds Number Range**

| Meter Number | Meter Type | Nominal Size (m) | Nominal Beta | Upstream Length (m) | Min Re | Max Re |
|---|---|---|---|---|---|---|
| 1 | Venturi | 8 | 0.4 | 2.027 | 94 | 8268 |
| 2 | Venturi | 8 | 0.6 | 2.027 | 84 | 9213 |
| 3 | Venturi | 6 | 0.4 | 1.540 | 285 | 6081 |
| 4 | Venturi | 6 | 0.75 | 1.540 | 391 | 9781 |
| 6 | Venturi | 4 | 0.6 | 1.022 | 88 | 11404 |
| 7 | Venturi | 4 | 0.75 | 1.022 | 208 | 14600 |
| 8 | QE Orifice | 8 | 0.45 | 2.393 | 647 | 9140 |
| 9 | QE Orifice | 8 | 0.6 | 2.393 | 240 | 7681 |

### 4.3 Test Results

Figures 9-13 show the discharge coefficient versus Reynolds number curves for meters 1-9 shown in Table 3 separated by meter type and nominal pipe size. Owing to the shape of the curves generated, there is no single curve that sufficiently represents each meter (except β=0.4 Venturis). For each meter a curve was fitted to each flow regime i.e. one for laminar and one for turbulent. During transition, a simple assumption that the discharge coefficient would be an average of the two curves was used. More complex algorithms can be applied. It is important to note that the point of transition from either laminar to turbulent or vice versa is not constant for a particular meter but is dependent on the current operating conditions i.e. the transition point will change from laboratory to the field.

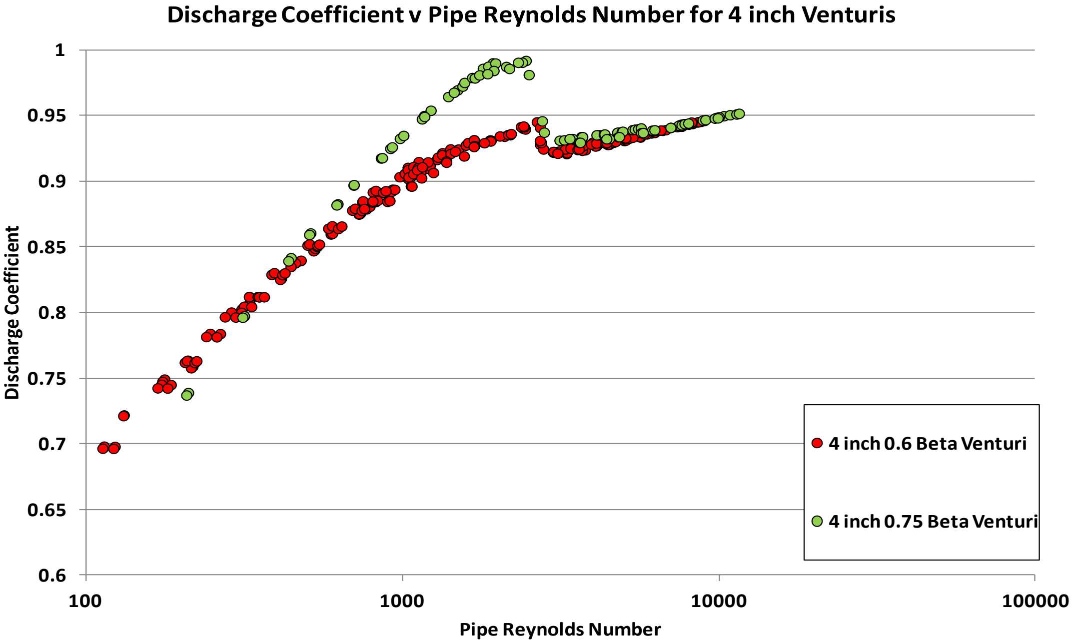

Figure 9: Discharge coefficient versus Reynolds number for 4 inch Venturis

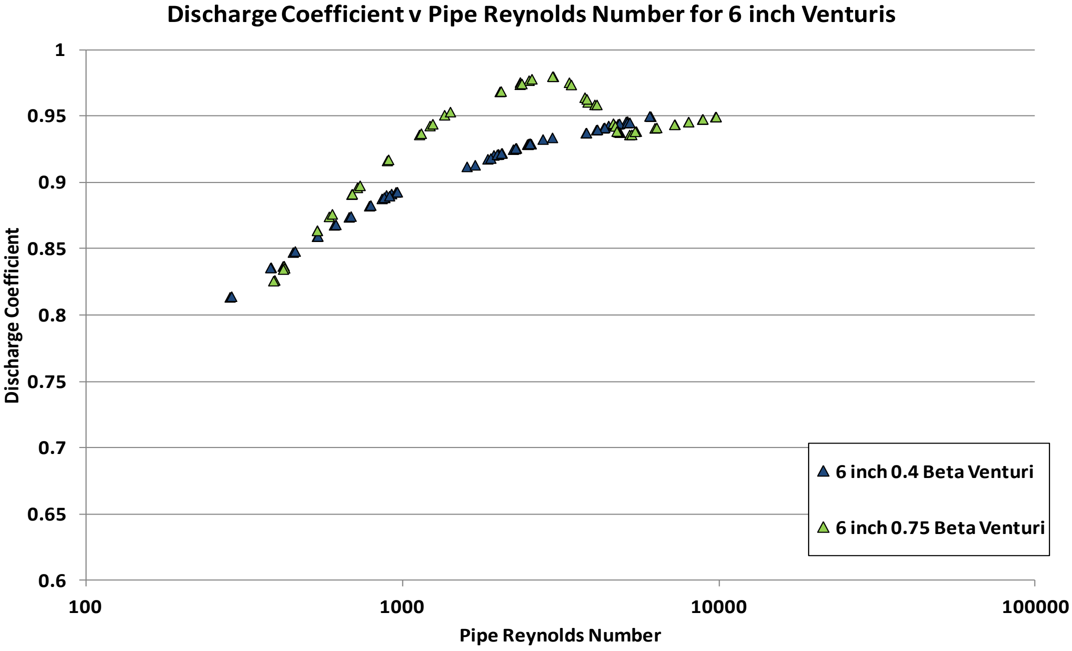

Figure 10: Discharge coefficient versus Reynolds number for 6 inch Venturis

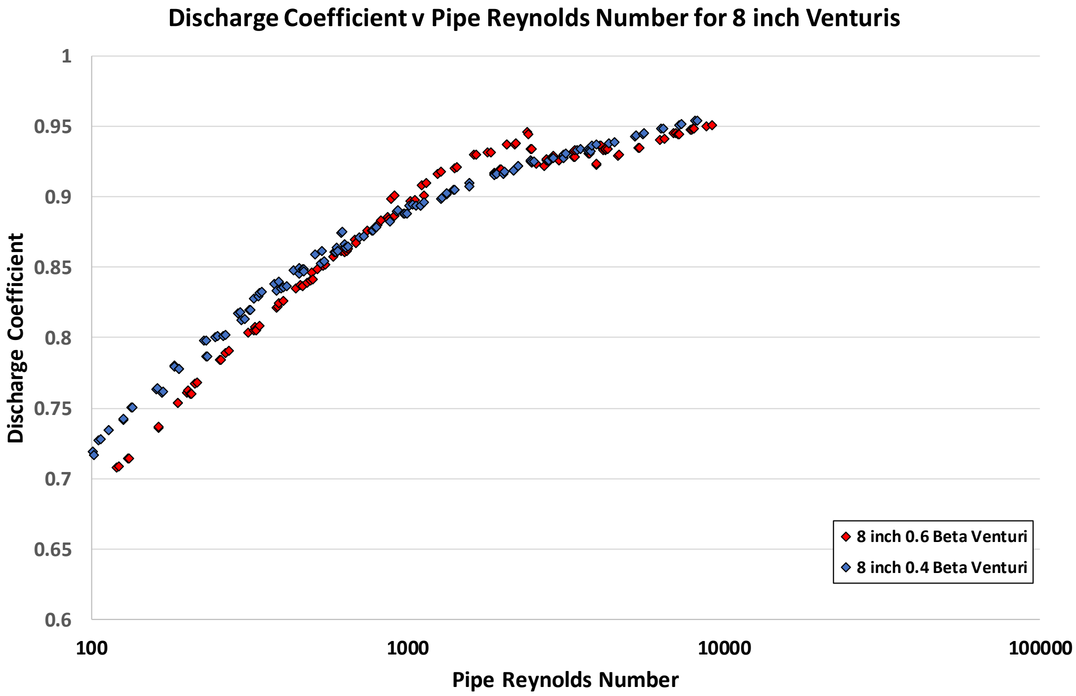

Figure 11: Discharge coefficient versus Reynolds number for 8 inch Venturis

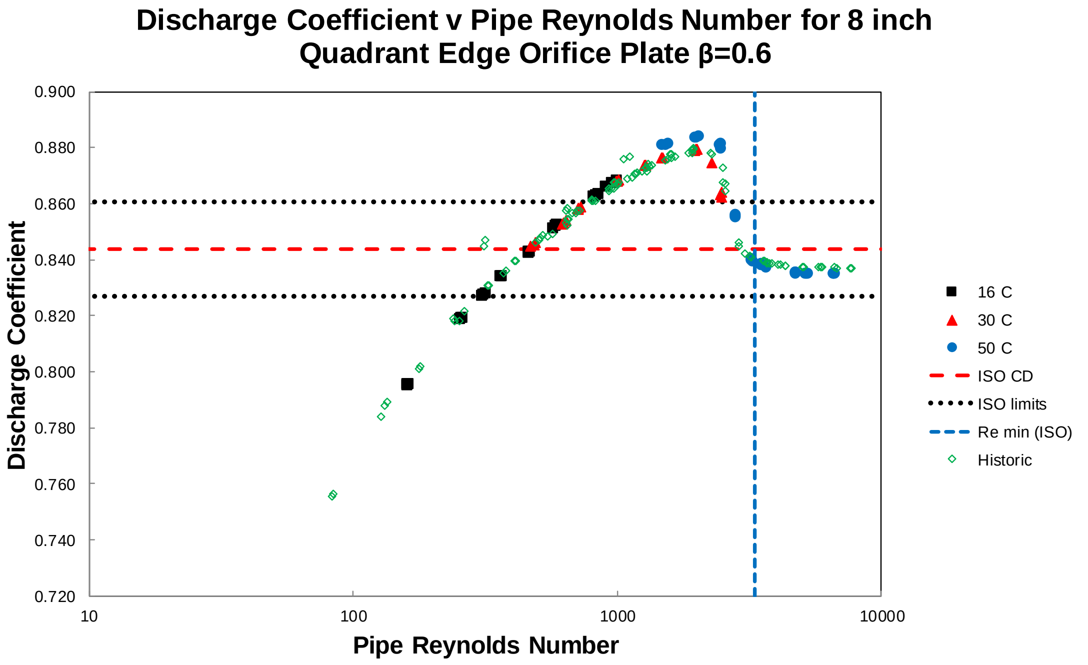

Figure 12: Discharge coefficient versus Reynolds number for 8 inch β=0.6 QE orifice plate

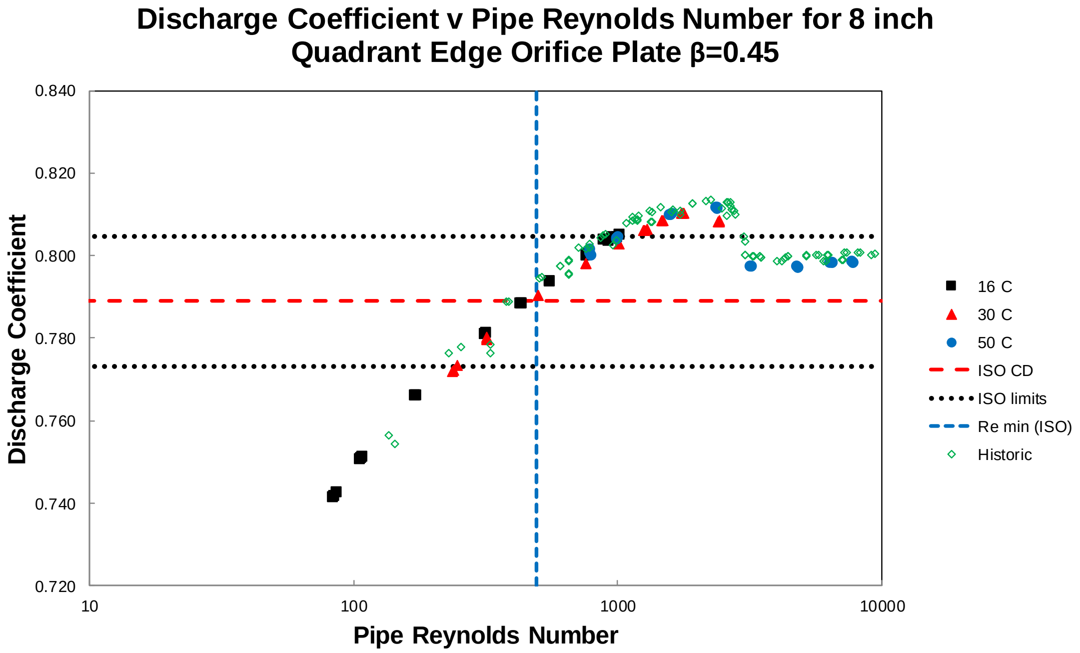

**Figure 13: Discharge coefficient versus Reynolds number for 8 inch β=0.45 QE orifice plate**

For the Venturi meters there is a clear trend in results that all meter geometries follow. Reducing Reynolds number from 10,000 shows a gradually decreasing discharge coefficient until the fluid reaches the transition point. In the majority of the cases shown this is around a Reynolds number of 3,000 – 4,000. At this point, there is a sharp increase in discharge coefficient (hydraulic hump); the magnitude of this increase is proportional to beta where a larger beta results in a larger increase. Once the discharge coefficient reaches a maximum ~2,000 Reynolds number it begins to decrease again in a steeper manner.

Noticeable differences from the above generic description is shown in Figure 10 for the 6 inch β=0.75 Venturi where the start of transition appears at a larger Reynolds number. The increase in discharge coefficient is no longer sharp and is indicative of a larger transition region than seen in the 8 or 4 inch tests.

In addition, the results of the β=0.4 Venturis show a removal of the increase in discharge coefficient completely. This suggests that smaller betas help smooth out the change between different flow regimes. Considering the comparison of pipe to throat Reynolds numbers around the transition point suggests that lower betas will reduce the effect of changing flow regimes i.e. there is a larger Reynolds range where the pipe will be laminar and the throat will be turbulent.

For the orifice plates shown, both show similar trends in results that mimic the Venturi data only at different magnitudes. Both plates have a linear discharge coefficient in turbulent flow giving credence to the claimed performance in low Reynolds numbers. At some critical Reynolds number, there is an increase in discharge coefficient that reaches a maximum and then reduces with further reducing Reynolds number.

The vertical dotted line (blue) in Figures 12 and 13 indicates the minimum Reynolds number the discharge coefficient equation found in [9] can be applied for that meter geometry. The horizontal dashed line (red) is the value expected from [9] for discharge coefficient and the horizontal dotted lines (black) are the 2% uncertainty in the discharge coefficient calculation.

Again, the larger beta provides a larger increase in discharge coefficient at transition, similar to the Venturis. For the β=0.6, the increase occurs below the minimum Reynolds number and the meter performs as expected from the specification in [9]. For the β=0.45, the increase in discharge coefficient occurs above the minimum Reynolds number and some discharge coefficient values fall outside the 2% uncertainty bands. This indicates that the equations found in [9] may not meet the stated performance levels and should be reviewed. It is thought the equations were derived from data acquired in the 1940’s which has subsequently been lost. With indications that 1,000 meters per year are sold to industry and which relies on this standard being correct, a thorough is justified.

Concentrating on the 8 inch β=0.6 quadrant edge orifice plate, and applying the new method shows some interesting results. For laminar flow, the discharge coefficient was fitted to an exponential function of Reynolds number and turbulent flow utilised the equation in [9] with an offset applied. The Reynolds number itself was calculated from equation 8 for laminar flow and the Colebrook-White equation (equation 9) for turbulent flow. A surface roughness of 0.05 mm was assumed.

Figure 14 shows the friction factor versus Reynolds number for a variety of calculation methods. From the reference data recorded, the new calculation method (equation 6) provides the same numerical answer as using the Darcy-Weisbach equation (equation 3). However, in comparison to theory i.e. equations 8 and 9, there are errors.

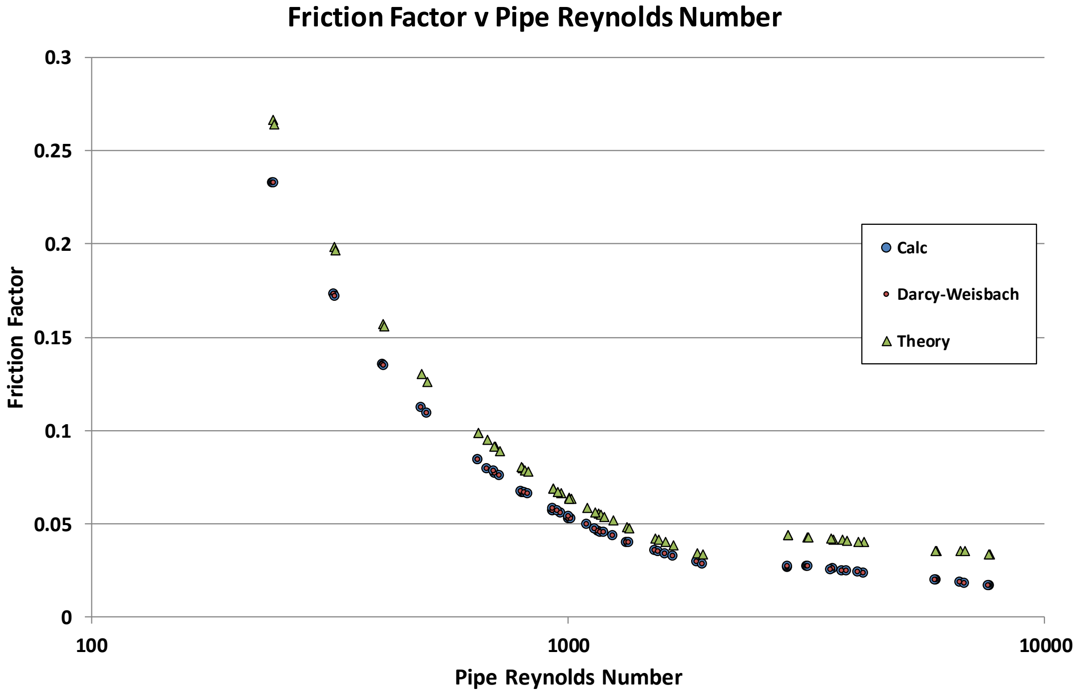

Figure 14: Friction factor versus Reynolds number for three different calculation methods

The error in the calculated friction factor is repeatable in both laminar and turbulent flow and can be corrected to remove the bias. It is important to note the new method under predicts in both laminar and turbulent flows with turbulent flow being significantly larger.

Having the ability to calculate friction factor and therefore Reynolds number, and knowledge of the correlation between discharge coefficient and Reynolds number it is possible to iterate the three to satisfactory solutions.

Figures 15, 16 and 17 show the errors in the results for discharge coefficient, Reynolds number and volume flow rate versus Reynolds number using the new method. Knowledge of the fluid density is required for the flow rate calculation.

The error in predicted discharge coefficient is reasonably good across most Reynolds numbers with the majority of points within 0.2% error. However, below 3,250 Reynolds number there is a noticeable increase in error. Remember the minimum Reynolds number this orifice geometry is said to operate to is 3,250 so this error is justified. The reason for the increase in error is due to the hydraulic hump that causes and increase in discharge coefficient which is not captured in the ISO equation.

This emphasises the importance of operating meters within their stated ranges. In a typical field application, this plate could have been used outside its specified range very slightly which would introduce an almost 1% under-reading error in flow rate.

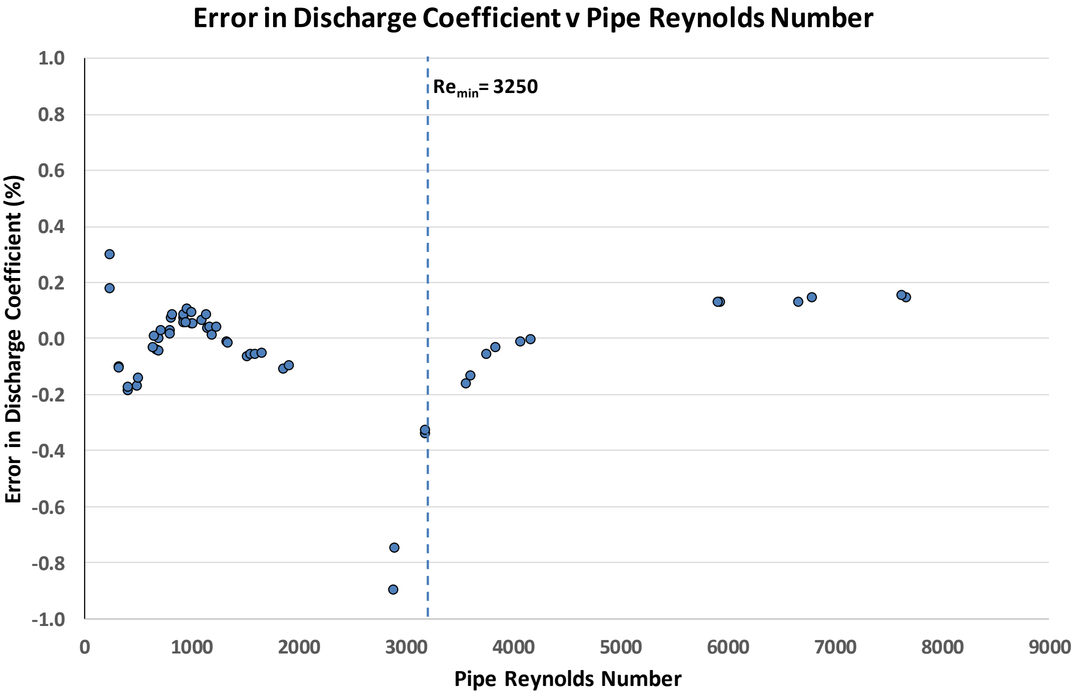

Figure 15: Error in discharge coefficient versus Reynolds number for 8 inch β=0.6 quadrant edge orifice plate

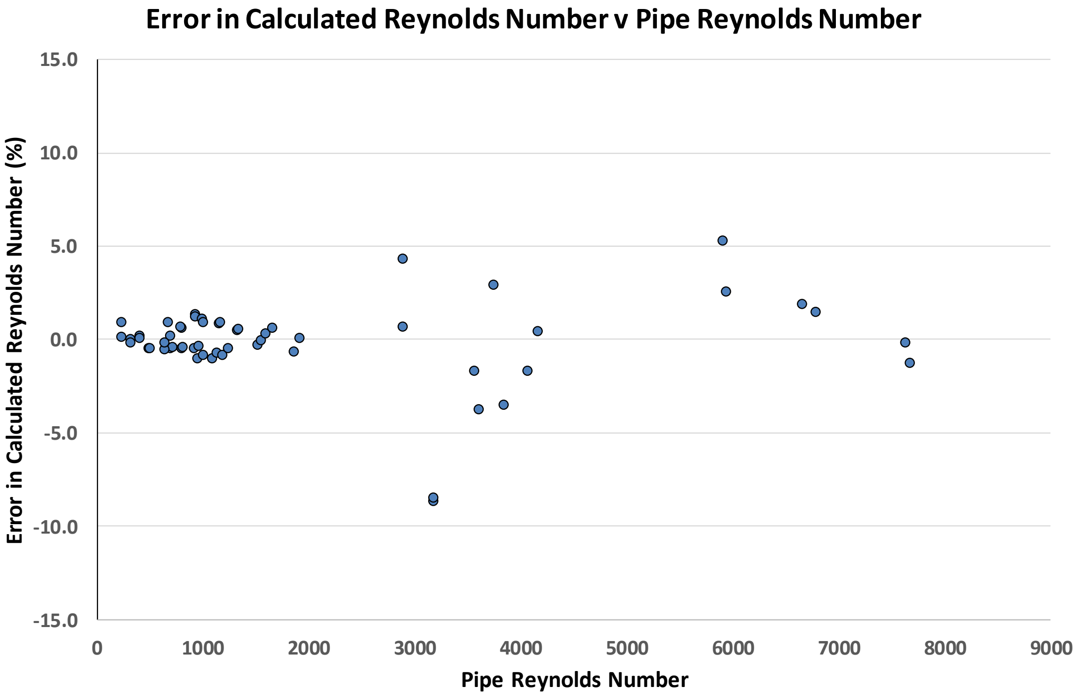

**Figure 16: Error in calculated Reynolds number versus Reynolds number for 8 inch β=0.6 quadrant edge orifice plate**

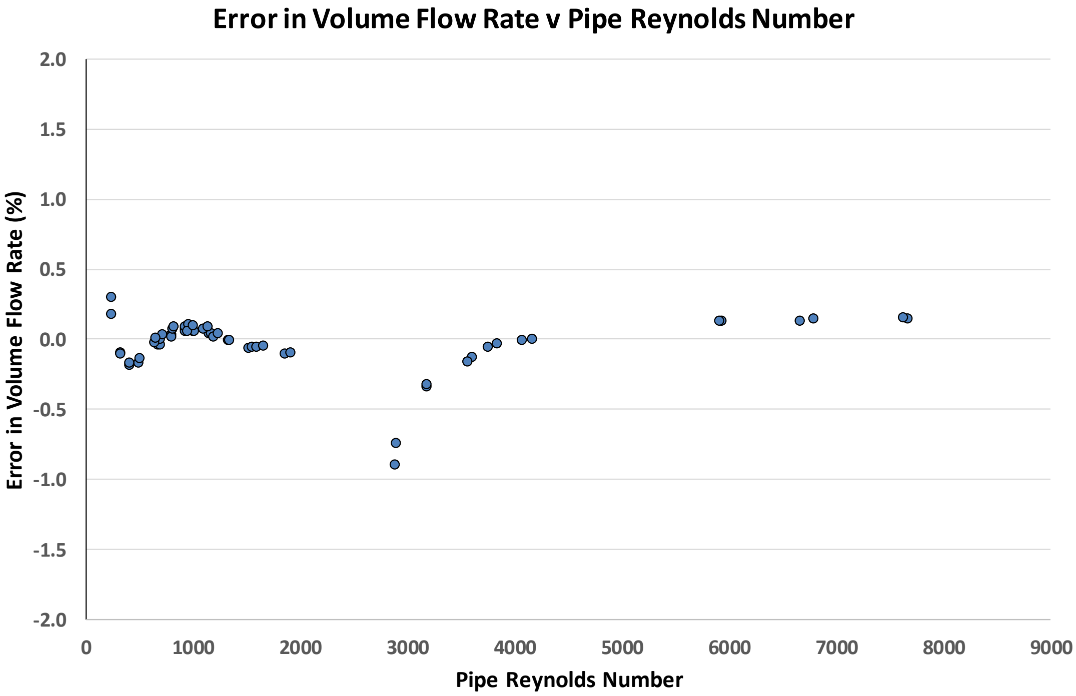

**Figure 17: Error in volume flow rate versus Reynolds number for 8 inch β=0.6 quadrant edge orifice plate**

The error in calculated Reynolds number is within 5% for all but 3 points. The error in laminar flow is better than turbulent flow with a much lower spread in results. In turbulent flow, the Reynolds number is derived using the Colebrook-White equation (applicable at Re>4,000) which has an uncertainty of 10%. Other simpler and more complex correlations are available but have not been applied to this data.

The error in volume flow rate is essentially similar to the error in discharge coefficient as the reference density was used in its calculation. Other parameters are essentially constants in the equations.

Taking the results further with the inclusion of a liquid clamp-on ultrasonic meter, it is also possible to calculate the physical properties in real-time creating a 3-in-1 meter. Calibrating the clamp-on ultrasonic meter against Reynolds number allowed for the uncertainty in velocity measurement to be reduced

The velocity measurement was then used to calculate the density of the fluid from equation 10, which was then used in another calculation of volume flow rate. Figures 18, 19 and 20 show the errors in calculated density, volume flow rate using the calculated density and the fluid viscosity versus Reynolds number respectively.

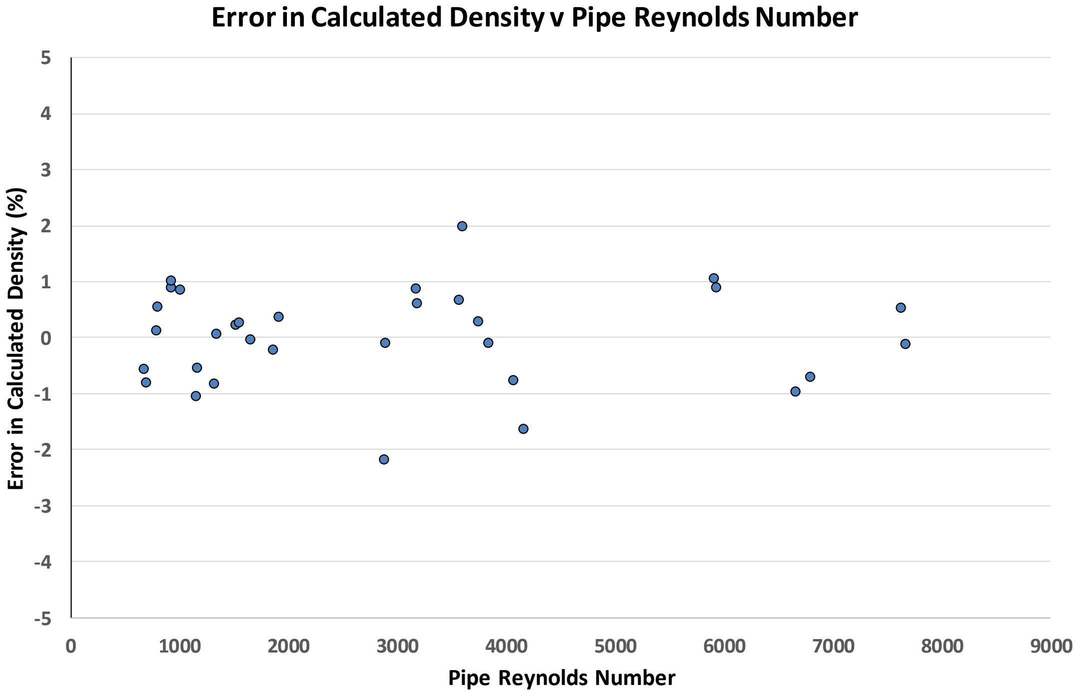

**Figure 18: Error in calculated density versus Reynolds number for 8 inch β=0.6 quadrant edge orifice plate**

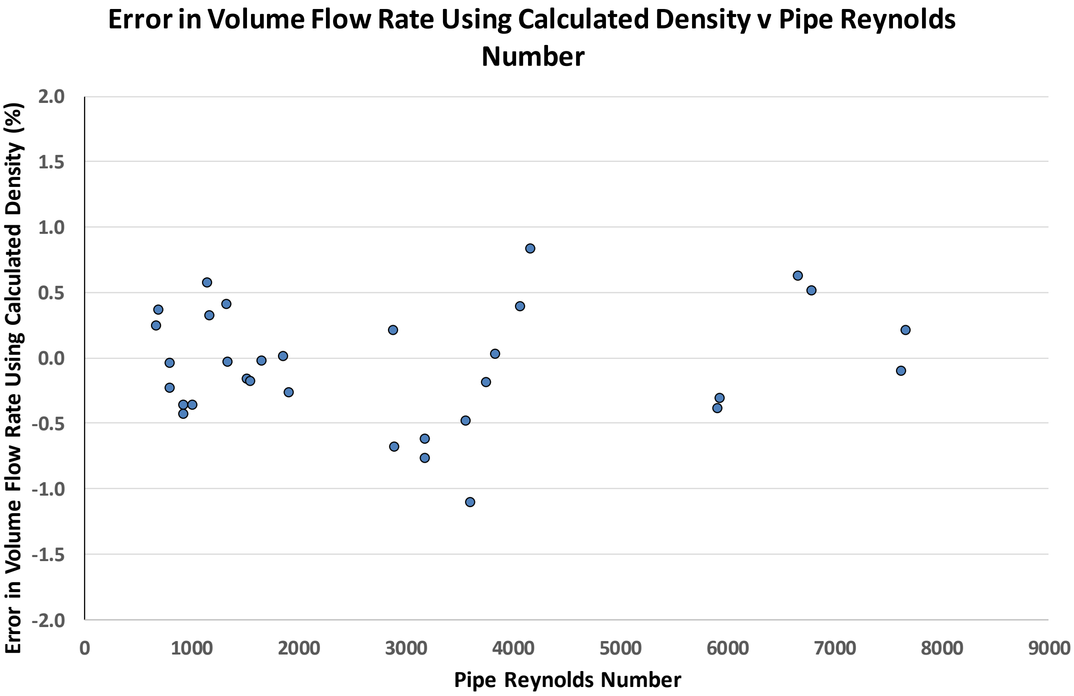

**Figure 19: Error in volume flow rate using calculated density versus Reynolds number for 8 inch β=0.6 quadrant edge orifice plate**

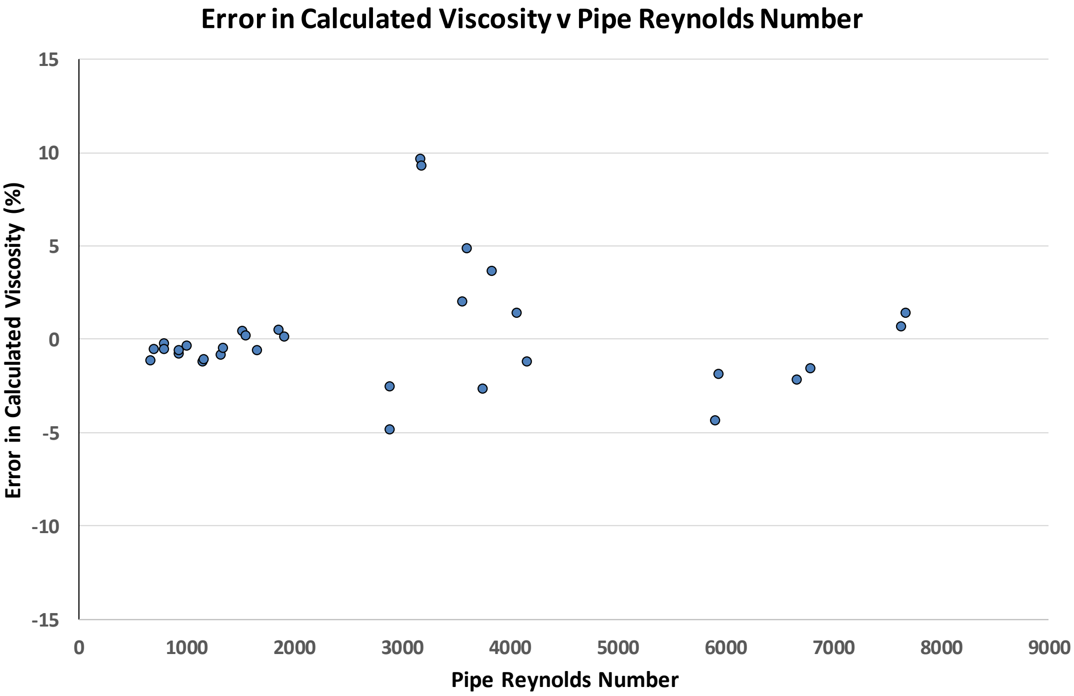

**Figure 20: Error in calculated viscosity versus Reynolds number for 8 inch β=0.6 quadrant edge orifice plate**

The error in density is within 2% with the major contribution to this error being the clamp-on ultrasonic meter. Using a more accurate device will result a reduced error.

The error in volume flow rate using the calculated density is within 1% with the majority of points within 0.5%. The larger errors associated with the discharge coefficient are not as noticeable in this examples as the error is density has worked to counteract its effect.

Lastly, the errors found in the calculation of dynamic viscosity are essentially mirror images of the error in calculated Reynolds number with that being the major component in its calculation. Again, the majority of calculated viscosity errors are within 5% of the reference value.

## 5 DISCUSSION

One of the primary measurement issues in low Reynolds number applications is the dependence of the performance index (e.g. discharge coefficient, K Factor, Meter Factor etc) on the Reynolds number itself. With a non-linear performance index any errors in the assumed Reynolds number can result in large errors in flow rate. This is true for the majority of flow measurement devices including differential pressure, turbines, Coriolis and ultrasonic meters. The difficulty comes through a requirement to know Reynolds number in order to apply the appropriate correction. However, if Reynolds number is known, then the user will probably have knowledge of flow rate already and therefore may not require the flow meter in the first place.

This new measurement method alleviates this problem by offering real-time knowledge of Reynolds number resulting in a more accurate performance index e.g. discharge coefficient for differential pressure meters, that can be applied to correct the flow rate. This paper has focussed on differential pressure flow meters but the theory can be applied to any technology that causes a repeatable, reproducible and measureable pressure drop caused by a restriction in the flow to offer a Reynolds number correction.

The method is based on a pressure loss over a straight length of pipe. To achieve a measurement with low uncertainty, it is advantageous for the pipe pressure loss to be as high as possible to increase resolution and reduce the turndown effect (zero errors). From equation 3, the only parameter that is variable for each installation is the length of pipe, $L$. A larger $L$ results in a larger pressure drop and therefore $L$ must be sized to ensure a measurable pressure drop is achieved with low uncertainty. Fortunately, in highly viscous fluids, the pipe pressure drop is larger than in less viscous fluids which can reduce the pipe length required.

In these tests, a pipe length of at 10 $D$ was included with reasonable results. Considering standard installation recommendations for upstream straight lengths of pipe of differential pressure meters, this value is certainly not excessive.

Another factor for discussion is on the critical Reynolds numbers for transition from laminar upwards and turbulent downwards. As discussed, this is not a fixed number and will vary from fluid to fluid, temperature to temperature and installation to installation. A full understanding of this phenomena is not yet available. The fact that this point is not static though puts in to question current calibration methods.

The current practice is to calibrate a meter over a specified range to determine is performance. The assumption is then that the meter will operate the same way in operation. One method of removing the effects of different fluids, physical properties, temperatures etc is to calibrate against Reynolds number. From empirical data and theory, matching Reynolds number is a valid method and results with low uncertainty can be obtained. This works in higher Reynolds numbers as the characteristic performance of the meter does not change at the same Reynolds numbers created from different conditions i.e. the relationship is fixed.

In lower Reynolds number, and specifically in the transition region, the relationship is not fixed and can change depending on the critical Reynolds number when entering transitional flow. For differential pressure meters, this means that performing a calibration in one fluid and deriving the discharge coefficient relationship with Reynolds number may not be valid over a small range. For instance, if during the calibration the transition region was found to be 2,100-3,000, and in operation it was found to be 2,500 – 4,500, then there would be a mis-match to some degree of calibrated discharge coefficient to the actual discharge coefficient. Fortunately, this would only be a small range and any error would be proportional to the differences between laminar and turbulent flow performance and hence a function of beta.

Operation of this new method in higher Reynolds numbers (without the additional technology) becomes less practical as friction factor approaches the fully turbulent line of the Moody plot (Figure 4). The sensitivity of determining Reynolds number from friction factor becomes lower until Reynolds number is entirely independent of friction factor. However, when this occurs, the Reynolds number is sufficiently high that the discharge coefficient tends to attain linearity again and Reynolds effects become negligible (compared with low Reynolds number applications) i.e. there is no significant need for knowledge of Reynolds number to counter Reynolds effects.

The inclusion of another measurement technique into the system offers additional advantages across a wide range of Reynolds numbers. In this paper, a clamp-on ultrasonic meter was used but any other velocity or density measurement device could be substituted with similar results. In low Reynolds number applications, this will provide both density and viscosity of the flowing fluid in real-time which offers substantial benefits to end-users.

Lastly, there are still areas of research to explore for this new method which will be conducted in the near-future. Specifically, more focus will be placed on:

- Critical Reynolds number effects e.g. changing fluids
- Developments in higher Reynolds numbers
- Combining the method with other technologies
- Developments in two and three phase flows
- Development of standard equations in laminar flow
- Investigating equations in ISO 15377:2007
- Calculation of uncertainty

## 6 CONCLUSIONS

This paper has presented a new method, based on differential pressure measurements, to provide a Reynolds number correction for flow meters. The focus has been on differential pressure meters due to the many advantages they offer which have led to a large market share in conventional applications. However, any intrusive flow meter offering a repeatable, reproducible and measureable pressure drop can use the method.

Heavy oil production is an important application for future energy needs with a lot of associated measurement challenges. In heavy oil production, there are huge measurement requirements from general process measurement through to fiscal level accuracy. Specifically, there is a need for a cost effective general process measurement device with uncertainty in the region of 2% and this new method can offer a solution to fill this gap.

For the meter presented, the error in Reynolds number was within 5%, the error in discharge coefficient was within 0.2% and the error in volume flow rate was within 0.2% (using a known density).

Utilising an additional measurement technique in combination with the new method provides calculation of fluid density to within 2%, fluid viscosity to within 5% and volumetric flow rate to within 1% (using the calculated density).

There are areas of development to deliver a complete solution in low Reynolds numbers using this method but the work presented highlights its current capabilities.

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