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Technical Paper

Advances in Flow Measurement Using a Frictional Pressure Drop

Craig Marshall, TUV SUD NEL

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1 INTRODUCTION

1.1 Reducing Costs in Measurement

In recent years, the oil and gas industry has sought to improve measurement technology to help reduce costs and increase operational efficiency. In terms of measurement accuracy, inline flowmeters are approaching the level of uncertainty of national standards so it is unlikely that there will be step change in measurement performance.

The improvement therefore must come from a reduction in cost of ownership of measurement technology. This can be achieved through a mixture of reduction in capital costs (cost of sale and installation) and reduction in operational costs (on going calibration and maintenance). The former is typically decided through market demand and with many manufacturers using similar materials; there should not be any major differences in prices for similarly performing systems.

For the reduction in operational costs, this has been achieved by the introduction of diagnostic systems that offer insight into the quality of the measurement of a device or devices. The majority of flowmeter technologies now have some form of diagnostics systems from traditional mechanical devices such and turbines and differential pressure meters through to more modern electronic systems such as Coriolis and ultrasonic meters.

There are many examples of the use of diagnostics in flow measurement and the benefit they can have for the end user in terms of understanding of their systems and cost reductions. However, some systems are more advanced than others by offering either more functionality or more diagnostic capabilities. This then, offers a potential differentiator for manufacturers of technology when making offerings to market.

The above description works well for individual measurement instruments but there is also potential for further reduction in maintenance and calibration costs when considering the whole measurement system. Consider a measurement system typically contains flowmeter, densitometer, pressure and temperature sensor as standard not to mention other instruments such as viscometers, gas analysers, etc. Each sensor has to be verified and maintained to ensure accuracy.

By reducing the number of sensors in a system, it would greatly reduce the effort and costs involved with maintenance. This method will involve making use of multi-parameter measurement devices where two or more process parameters are measured. Coriolis meters offer both flow and density as outputs and this has likely contributed to their acceptance and growth in the oil and gas industry in recent years.

Finding other methods to offer more than one measured process parameter in real-time would help industry achieve the goal of reducing costs and improving efficiency. A modular approach should be undertaken where both reducing the number of pieces of equipment used as well as having diagnostic capability would offer a more powerful cost reduction tool.

Of course, measurement uncertainty will play a key role in any adaptation of this kind. The overall system uncertainty specified in regulations, sales agreements or other will have to be adhered to. If a multi-parameter system does not meet this criterion then it cannot be used. However, there are many applications where a larger measurement uncertainty may be tolerated and its use could be fully justified.

In addition, for any new measurement system, the final uncertainty value would have to be calculated. Technology advances regularly and making use of these advancements may see systems offering multiple parameter measurements with similar uncertainty levels currently found with current state of the art.

1.2 Development of Frictional Pressure Drop Research at NEL

NEL has conducted flow measurement research for many years; developing new facilities to better accomplish objectives and solve problems. Over the past two decades, there has been a push within industry for development and production of unconventional hydrocarbon resources including heavy oils and bitumens. Heavy oils are known to have a larger viscosity compared with conventional resources and as such have a number of process challenges associated with them. One such challenge, amongst others, is in the fluid flow measurement performance owing to the Reynolds number range covered.

In the late 2000's, NEL designed and commissioned a high viscosity flow facility at the laboratory in East Kilbride. The facility has subsequently undergone upgrades and can now accurately measure the flow rate of fluids up to 1500 cSt. This facility is ideal for conducting flow measurement research on viscous fluids representative of heavy oils found during production.

The performance of flowmeters under these conditions has been presented numerous times previously and all provide similar conclusions that are summarised as follows:

1. The performance index of a flowmeter is dependent on Reynolds number with the rate of shift in performance increasing with decreasing Reynolds number.
2. The performance index generally decreases with decreasing Reynolds number.
3. The performance index is repeatable and reproducible.
4. Flowmeters should not be calibrated in one fluid and used in another if the Reynolds number range is significantly different.
5. Calibration method needs to be assessed when the Reynolds number range covers the transition region as the critical Reynolds number for transition may change between laboratory and field.

The fact that flow meters tend to be repeatable and reproducible against Reynolds number allows for correction factors to be implemented to correct the measured result. However, in order to implement the corrections, the real-time operational Reynolds number needs to be known – something that could only be known if the flowrate or velocity was known. That is where the challenge for this application fully comes to light. For consistent accuracy, an iterative solution is used that requires accurate knowledge of real-time fluid physical properties and measurement of flowrate.

Linking back to the previous section, a requirement of density, viscosity and flow measurement in order to achieve a low uncertainty results in three separate measurement devices that have to be procured, installed and maintained on an on going basis. This cost can be extremely prohibitive to end users, especially in heavy oil production where the extraction costs per barrel are larger than conventional oil and gas. The result is often a sub-standard measurement system that includes many assumptions or constants instead of measuring system parameters.

As discussed, NEL conducts research in flow measurement covering a wide variety of topics. One such project was focussed on heavy oils with the objective of finding a simple solution to measuring operational Reynolds number in real-time. The flowmeters investigated were Venturis and the results were published after the project was complete.

The most promising method developed has been taken forward as the subject of an engineering doctorate project. The initial development focussed on differential pressure flowmeters only and was presented at last year's NSFMW. The method had moved on significantly from the original project and additional data on quadrant edge orifice plates were also included. Differential pressure meters were chosen as the primary technology owing to their cost, ease of use and their large market share in higher Reynolds number applications that was not mirrored in low Reynolds number ones.

Further work has been completed with different metering technologies that offer additional advantages over differential pressure meters. Including turbines and Coriolis flowmeters offers the development as a modular system balancing cost, accuracy and uncertainty for the measurement of flow, density and viscosity.

1.3 Objectives

The objectives of this paper are to:

1. Present the results of the developed method with other measurement technology
2. Discuss the advantages and disadvantages of the method will different measurement technology
3. Highlight the limitations and expected uncertainty estimates of the method.

2 THEORY

Consider the set-up as shown in Figure 1 where flow enters from the left hand side. The pressure loss over a straight piece of pipe with no restriction is measured (ΔP_f) as well as the pressure loss over a restriction (ΔP_1). The restriction in this example is said to be any intrusive type flowmeter i.e. turbine meter, Coriolis meter, positive displacement meter, differential pressure meter etc. In the case of differential pressure meters, it is possible to measure the pressure drop through the primary element as opposed to the permanent pressure loss.

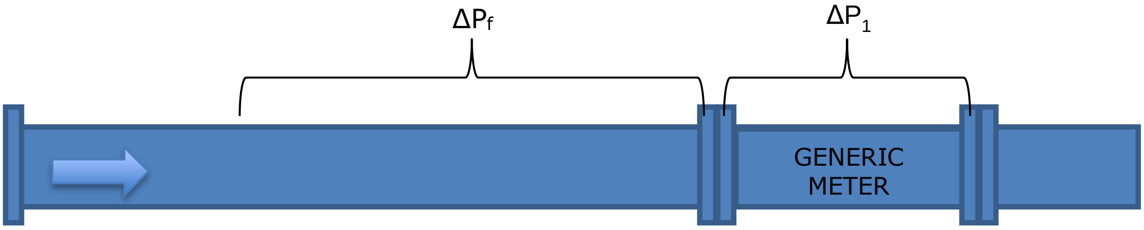

Figure 1: Generic system installation

The pressure loss along a straight length of pipe can be estimated through the Darcy-Weisbach equation as shown in Equation 1 (all notation is described in section 7).

$$\Delta P_f = \frac{\lambda \rho u^2 L}{2D}$$

Equation 1

The flowrate through the restriction can be written as shown in $Q_v = \frac{C_d \epsilon}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{\frac{2\Delta P_1}{\rho}}$

Equation 2. $Q_v = \frac{C_d \epsilon}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{\frac{2\Delta P_1}{\rho}}$

Equation 2 represents the flowrate through a restriction with circular cross-section such as a Venturi or orifice plate. This equation can be used with any restriction using assumed system geometry for d, D and β. A similar loss equation (not shown) can also be used.

$$Q_v = \frac{C_d \epsilon}{\sqrt{1-\beta^4}} \frac{\pi d^2}{4} \sqrt{\frac{2\Delta P_1}{\rho}}$$

Equation 2

Rearranging Equation 2 in terms of velocity and substituting into Equation 1 results in a new equation for friction factor that is independent of fluid physical properties, as shown in Equation 3. Equation 3 shows four terms; one a ratio of two differential pressure measurements, two a constant relating to meter geometry and pipe length (C_M), three the differential pressure meter discharge coefficient (C_d) and four the fluid expansibility (ϵ).

$$\lambda = \frac{\Delta P_f}{\Delta P_1} \frac{C_M}{{C_d}^2 \epsilon^2}$$

Equation 3

where

$$C_M = \frac{D(1-\beta^4)}{L\beta^4}$$

Equation 4

For low Reynolds number applications, especially in heavy oil applications, $\epsilon = 1$ will likely be valid. C_d will be determined through calibration or equation with low uncertainty e.g. Reader-Harris Gallacher equation from ISO 5167 for orifice plates. Equation 5 will be the practical implementation in heavy oil flows.

$$\lambda = \frac{\Delta P_f}{\Delta P_1} \frac{C_M}{{C_d}^2}$$

Equation 5

Once friction factor is calculated, Reynolds number can be acquired through Equation 6 and Equation 7 for laminar and turbulent flow respectively.

$$\lambda = \frac{64}{Re} \quad for\ Re \leq 2100$$

Equation 6

$$\frac{1}{\sqrt{\lambda}} = -2\log\left(\frac{r}{3.7} + \frac{2.51}{Re\sqrt{\lambda}}\right) \quad for\ Re \geq 2300$$

Equation 7

Lastly, discharge coefficient can be calculated through its relationship with Reynolds number. As discharge coefficient is included in Equation 5, an iterative calculation is required to converge on a solution for all three unknown parameters.

By measuring the pressure loss across the restriction and the separate pressure loss across the upstream length of pipe, and with knowledge of the pipe and restriction geometry, and a predetermined relationship between discharge coefficient and Reynolds number, it is possible to calculate friction factor independent of the fluid physical properties and therefore calculate Reynolds number in real-time. By using this method, any measurement device that causes a repeatable, reproducible and measurable pressure drop can have the effect of Reynolds number of the performance of the meter removed (within the calculation uncertainties). This applies to both restriction type meter (Coriolis, turbine etc.) output and the differential pressure based meter over the restriction.

For the calculation of flowrate (mass or volume) from the restriction differential pressure based meter, the density is required. Current practice attains this either through direct measurement with a densitometer or by laboratory analysis of a sample. Each method has a different uncertainty, cost and performance that are usually considered by the end user. However, as stated earlier, reducing the number of pieces of equipment can have significant benefit. Also, up to this point, the fluid properties have not been required in the calculations. In addition, having an estimate of the operational Reynolds number is something that has not been previously available without having knowledge of physical properties. This means that the calculation process can be revisited i.e. instead of using physical properties to calculate Reynolds number; the Reynolds number can be used to help calculate the physical properties.

It is possible to create a multi-parameter system with this development by including another measurement input. Previous work has shown the development operating with a differential pressure meter, which required a secondary input of velocity. Rearranging Equation 1 in terms of density shows that once friction factor is known, the only unknown in the equation is velocity (Equation 8). The only caveat is that the velocity estimate does not include a square root relationship with density e.g. $u \propto \rho^{-1/2}$ as with Bernoulli derivations.

$$\rho = \frac{2D\Delta P_f}{\lambda u^2 L}$$

Equation 8

In the case of differential pressure meters, the velocity estimate came from a clamp-on ultrasonic meter but any source would work. The choice obviously impacts the overall uncertainty. For other meter technologies, Equation 8 can be amended to be based on the input source. For instance, Coriolis meters output mass flowrate and turbines volumetric flowrate with the amended equations shown in Equation 9 and Equation 10 respectively.

$$\rho = \frac{8\lambda L {Q_m}^2}{\Delta P_f \pi^2 D^5}$$

Equation 9

$$\rho = \frac{\Delta P_f \pi^2 D^5}{8\lambda L {Q_v}^2}$$

Equation 10

Once density is known, by whatever means, the common Reynolds number equation can be rearranged to calculate viscosity as shown in Equation 11.

$$\mu = \frac{\rho u D}{Re}$$

Equation 11

Using this method with an intrusive flowmeter that provides its own measurement principle allows for the calculation of a Reynolds number corrected flowrate, an estimate of density and an estimate of viscosity. This is a further step forward from the work on differential pressure primary elements only as the additional flow or velocity measurement input no longer requires a separate measurement unit. Instead, by using the flowmeter as normal and including two differential pressure measurements, a multi-parameter system can be made that negates the need for multiple instruments.

Furthermore, if the density calculation can become independent of the meter flowrate input, a second flowrate measurement can be calculated that will not be linked to the first and can potentially be used in a comparative diagnostics system. As an example, instead of using the mass flowrate from a Coriolis meter, the density output could be used which would allow the differential pressure based flowrate calculation to be extrinsic from any errors in the Coriolis mass flowrate. Only then could the measurements be used in comparison. Of course, any factor affecting performance will cause errors in both measurements however, it is likely the magnitude of the error will be different.

Lastly, the development described above can be considered modular in that there are many configurations that would allow it to be implemented. The Reynolds correction method can be used with any intrusive meter type but the physical property calculations can be completed with an additional meter, the restriction measurement principle or by having a separate density meter. Each method of implementation will have a different uncertainty level and cost which offers flexibility for end users.

3 TESTING

3.1 NEL Oil Facility

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 inch to 8 inch, 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 2 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.

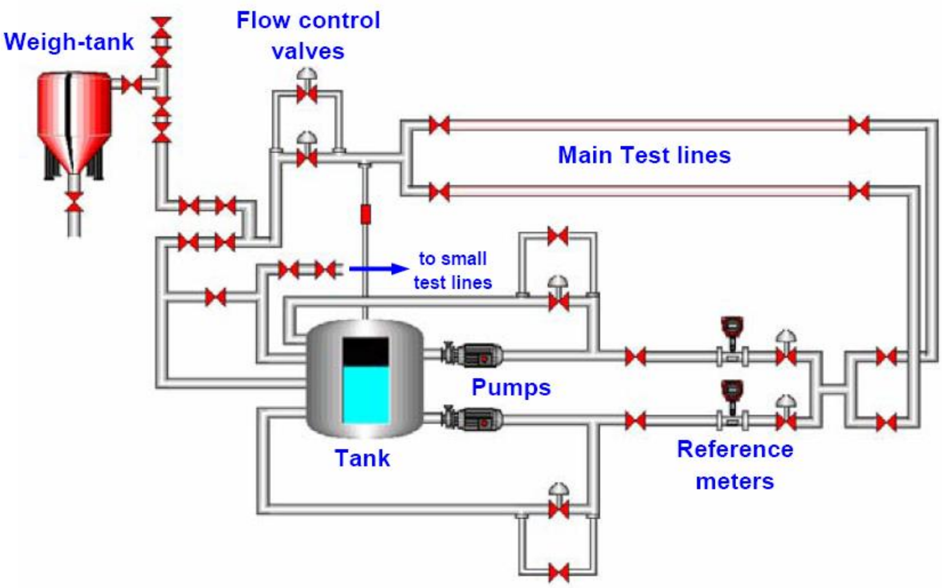

Figure 2: Schematic Diagram of the NEL Oil Flow Test Facility

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 fluids with viscosity up to 50 cSt and ± 0.05 % (k=2) thereafter.

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) for fluids with viscosity up to 50 cSt and ± 0.25 % (k=2) thereafter.

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 3**. 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.

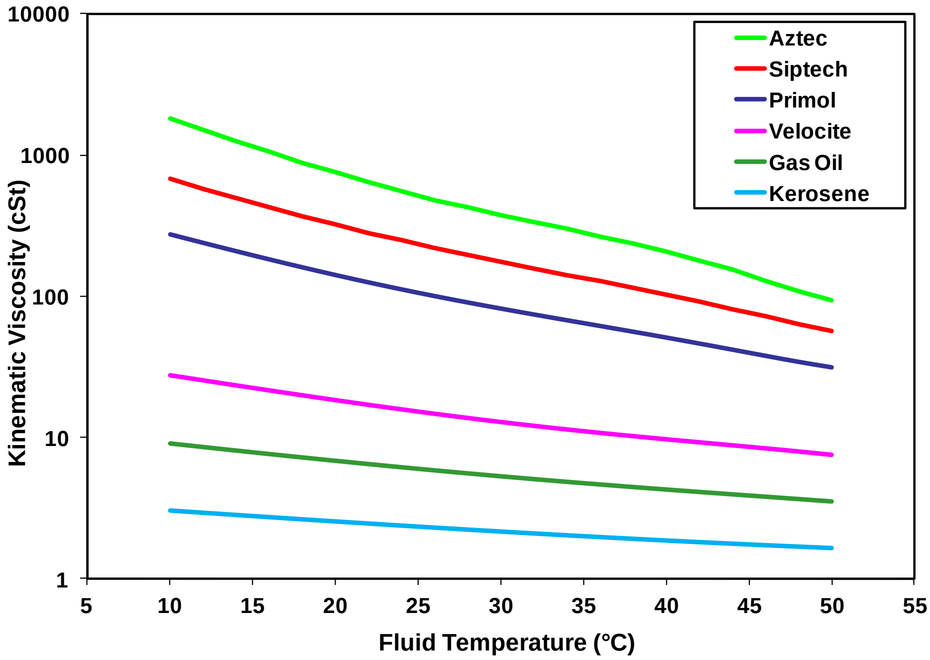

Figure 3: NEL Test Fluids

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%.

3.2 Coriolis Results

The method was tested on a 3 inch Coriolis meter that was installed in the NEL high viscosity test facility. The testing covered a Reynolds number range of 100 – 5000. The fluid was Aztec at 50 °C equating to a viscosity in the region of 130 cSt. **Figure 4** and **Figure 5** show the performance of the Coriolis meter versus mass flowrate and Reynolds number respectively.

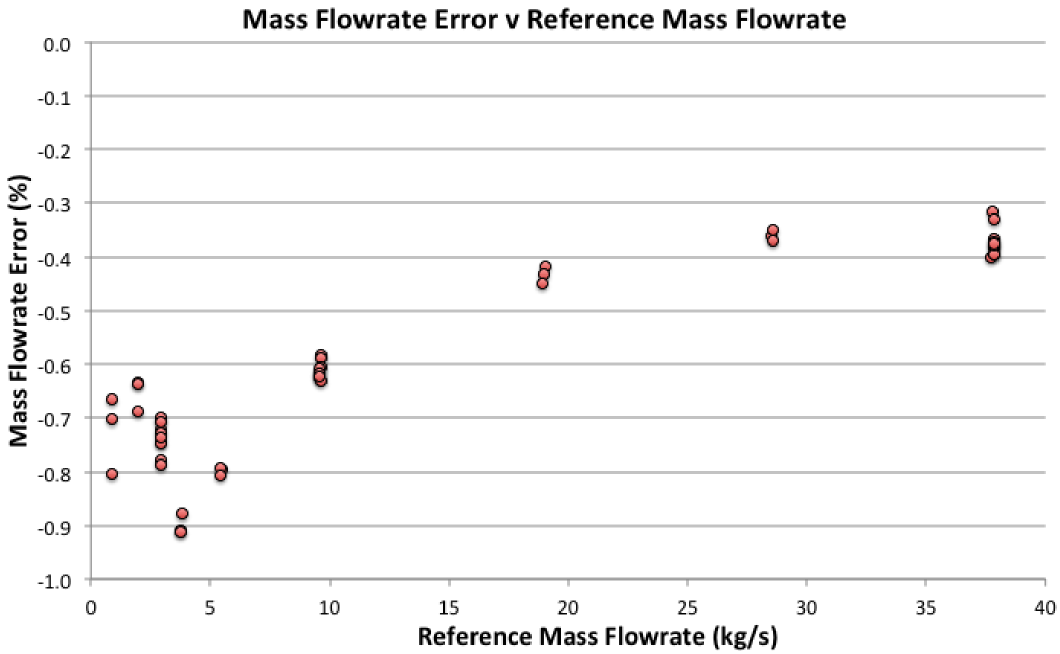

Figure 4: Coriolis performance v Mass flowrate

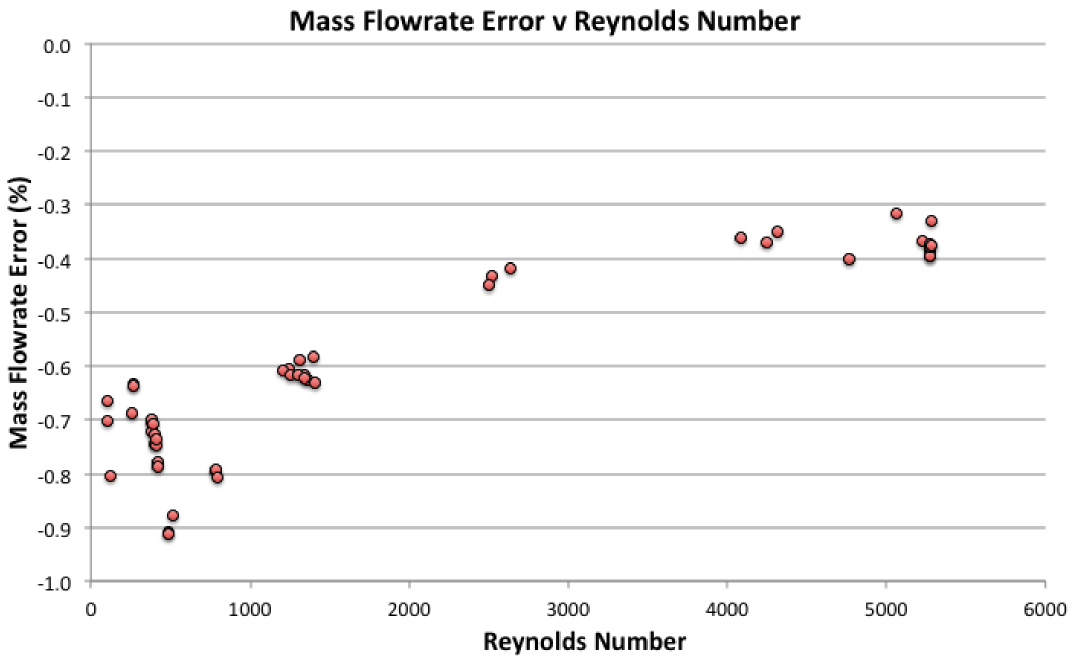

Figure 5: Coriolis performance v Reynolds number

The meter was not calibrated beforehand and no adjustment was made to the performance prior to this test. From **Figure 5** it is clear that there is a Reynolds number dependence on the Coriolis meter performance, which, if left uncorrected, could result in a 0.5% error in measurement. It is important to bear in mind that this error is only over a small range of Reynolds number. For instance, if the Reynolds span went up to 50,000 or even 100,000 then larger errors would be likely.

The equivalent velocity through the 3 inch pipe was between 0.2 – 10 m/s. Over the 1.5 m length upstream of the meter the measured pressure loss was in the range of 4 – 400 mbar.

The development can be applied in two different ways with the initial Reynolds correction stage the same for both. The divergence comes from the input parameter to calculate viscosity. In one method, Equation 9 can be used making use of the measured Coriolis mass flowrate output. The other method involves using the measured Coriolis density output.

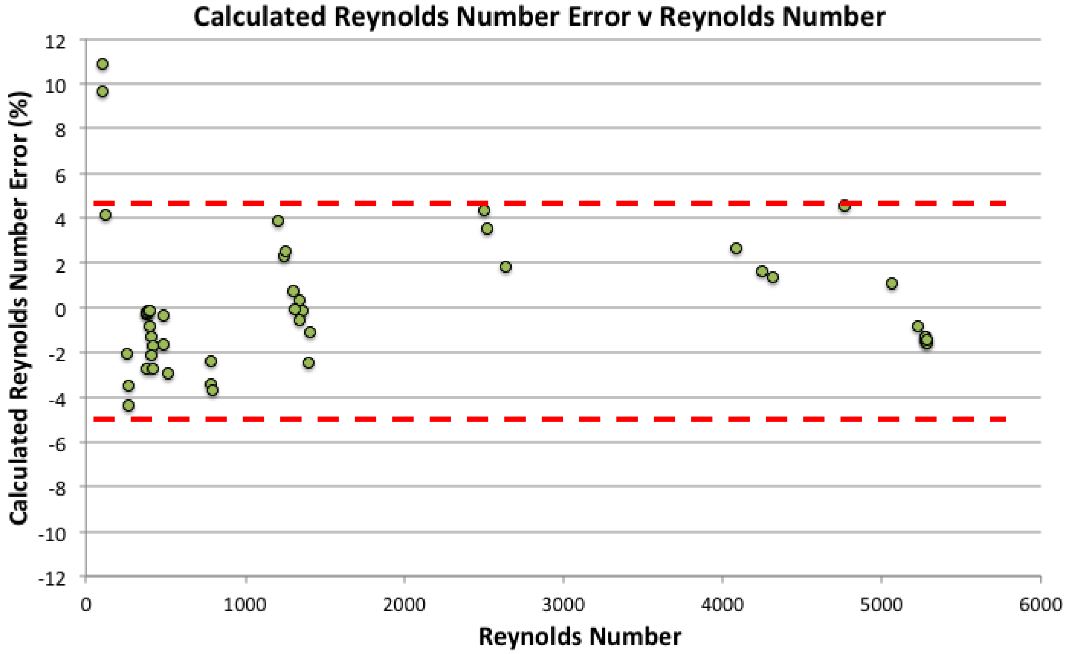

Figure 6: Calculated Reynolds number error v Reynolds number

Figure 6 shows the calculated Reynolds number error against the reference Reynolds number. For this meter the results fall within a band of ± 5%. **Figure 7** shows the error in calculated density using the Coriolis mass flowrate as an input. **Figure 8** shows the calculated mass flowrate error using this estimated density.

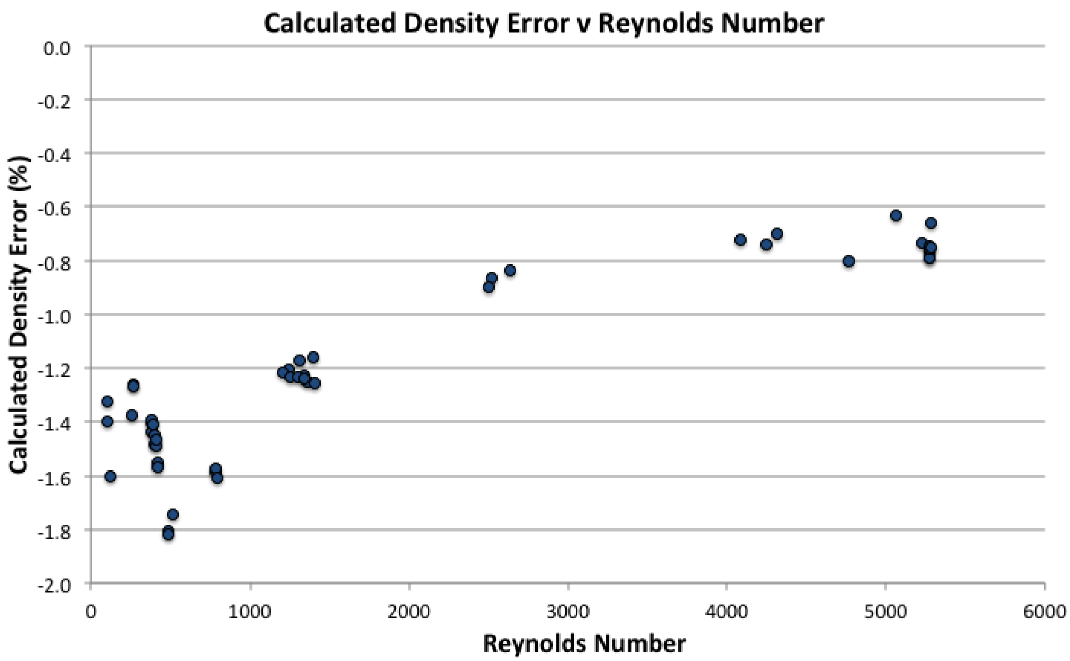

Figure 7: Calculated density error v Reynolds number using Coriolis mass flowrate

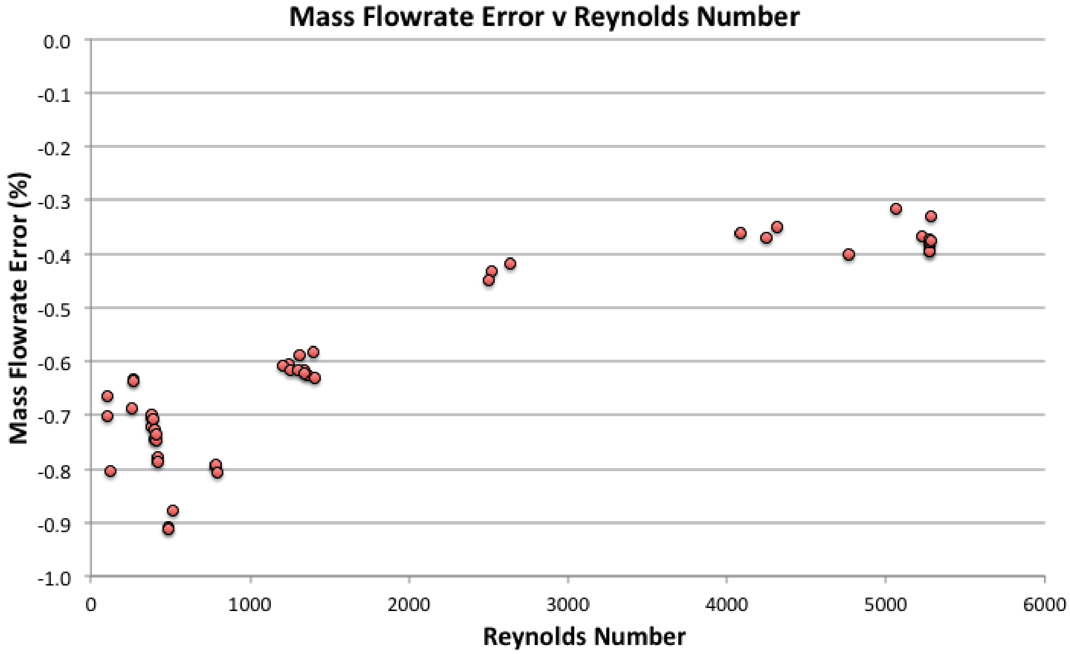

Figure 8: Calculated mass flowrate error of differential pressure meter v Reynolds number using calculated density

As the density is calculated using the mass flowrate from the meter, any errors from the flow measurement are translated into the density calculation. As such **Figure 7** has the same shape of curve as **Figure 5** only with the errors offset by a sensitivity of 2 given the square relationship. In addition, given the calculated density is proportional to the Coriolis mass flowrate, the differential pressure meter mass flowrate is found to be the same as the Coriolis when the calculation is made. This can also be found in the equations if Equation 8 and Equation 3 are substituted back into Equation 2.

This result brings into question the purpose of this new development if the mass flowrate calculations are the same. Firstly, there is still relevance to provide the real-time Reynolds number, which has already been described to be extremely important in low Reynolds number applications. Secondly, even without an additional flowrate indication the calculation of density and viscosity (see **Figure 9**) without the need for separate instruments is still an advantage.

Lastly, the results become related through the calculation of density only. If the density can be measured or estimated by another means, preferably one that is totally separate from the primary measurement method of the original meter, then it would be possible to have two separate flowrate measurements as well as the calculations of physical properties.

Figure 9 shows the calculated viscosity error found when completing the method on this meter. The results appear to be consistent and inverse of the Reynolds number errors, which is one of the primary sources of error in the calculation of viscosity. Again, the majority of test points are within ± 5%.

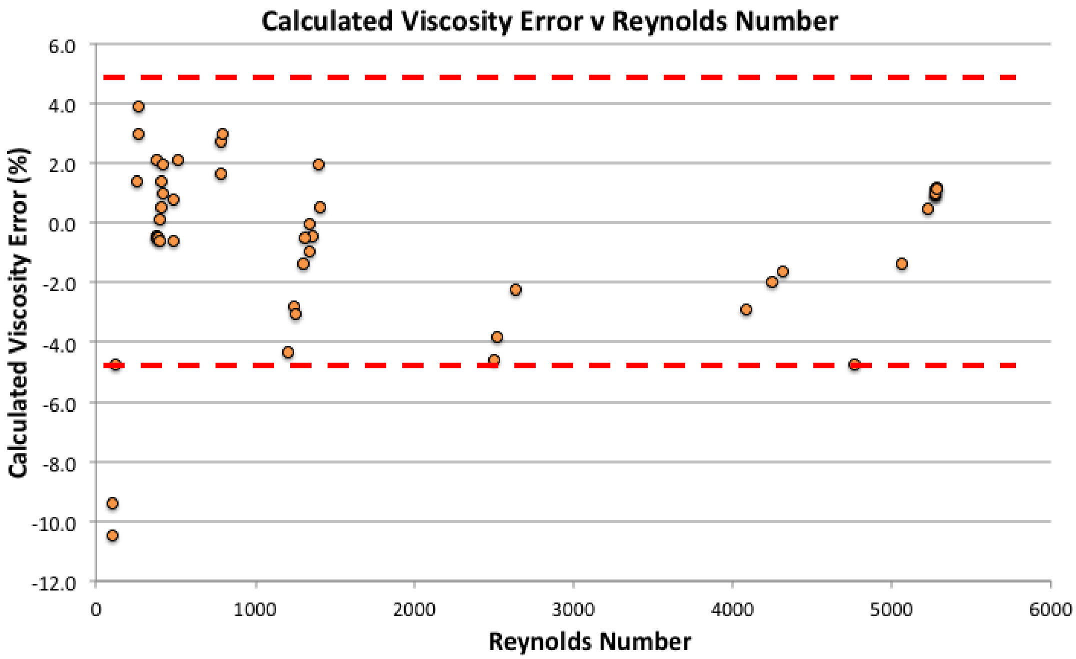

Figure 9: Calculated viscosity error v Reynolds number using calculated density

Instead of using the mass flowrate of the Coriolis meter to calculate density, the density output itself can be used. This negates the step of using Equation 8, Equation 9 or Equation 10. From previous NEL testing, the density output can be very good as shown in **Figure 10**. Although not totally extrinsic, the density measurement from the Coriolis can offer distinction from the Coriolis mass flowrate output.

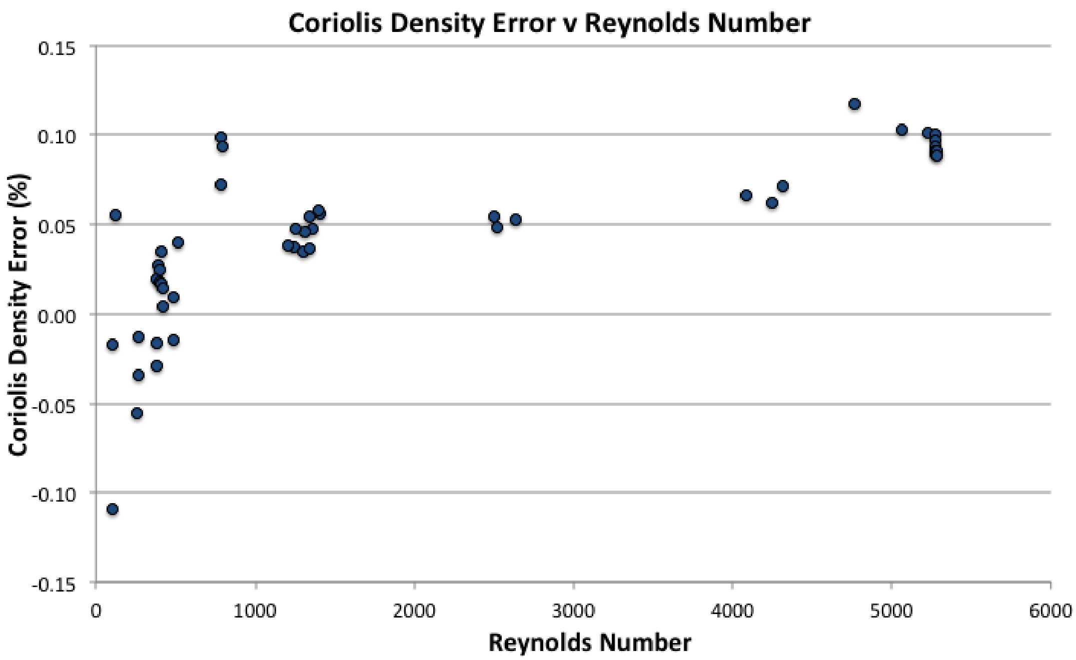

Figure 10: Coriolis density error v Reynolds number

Figure 11 shows the calculated mass flowrate of the differential pressure meter and **Figure 12** shows the calculated viscosity error using this method.

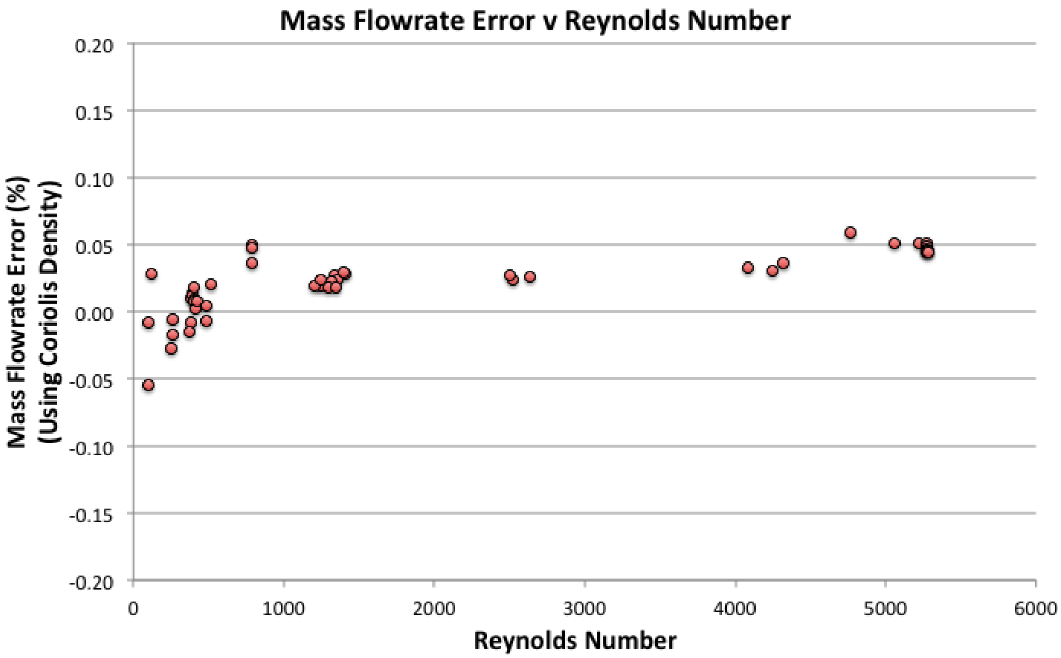

Figure 11: Calculated mass flowrate error of differential pressure meter v Reynolds number using Coriolis density

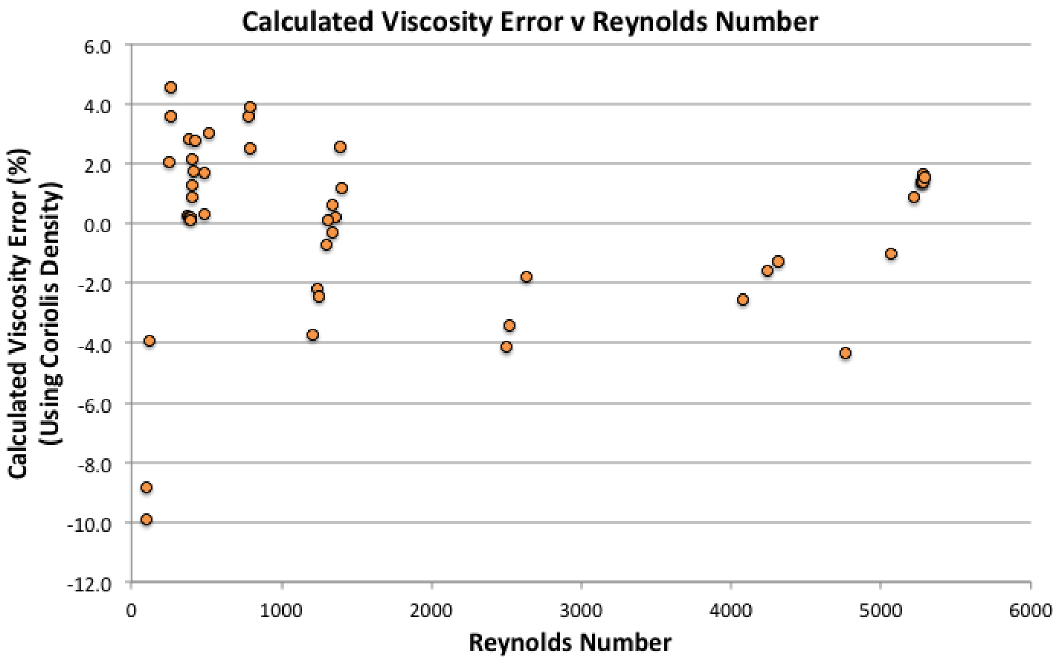

Figure 12: Calculated viscosity error v Reynolds number using Coriolis density

As the density measurement from the Coriolis is partially separate from the mass flowrate measurement, the two mass flow values are not correlated together. The second method provides better results than the first. This is primarily due to the density used in the calculation having a much better accuracy and lower uncertainty.

Interestingly, the viscosity calculation remains relatively unchanged. This shows the dependence on the Reynolds number estimate running through the calculation process.

3.3 Turbine Results

The method was tested on a 4 inch straight bladed turbine meter that was installed in the NEL high viscosity test facility. The testing covered a Reynolds number range of 400 – 8000. The fluid was Aztec between 35 and 50 °C equating to a viscosity between 110 to 340 cSt. **Figure 13** shows the performance of the turbine meter versus Reynolds number with respect to temperature.

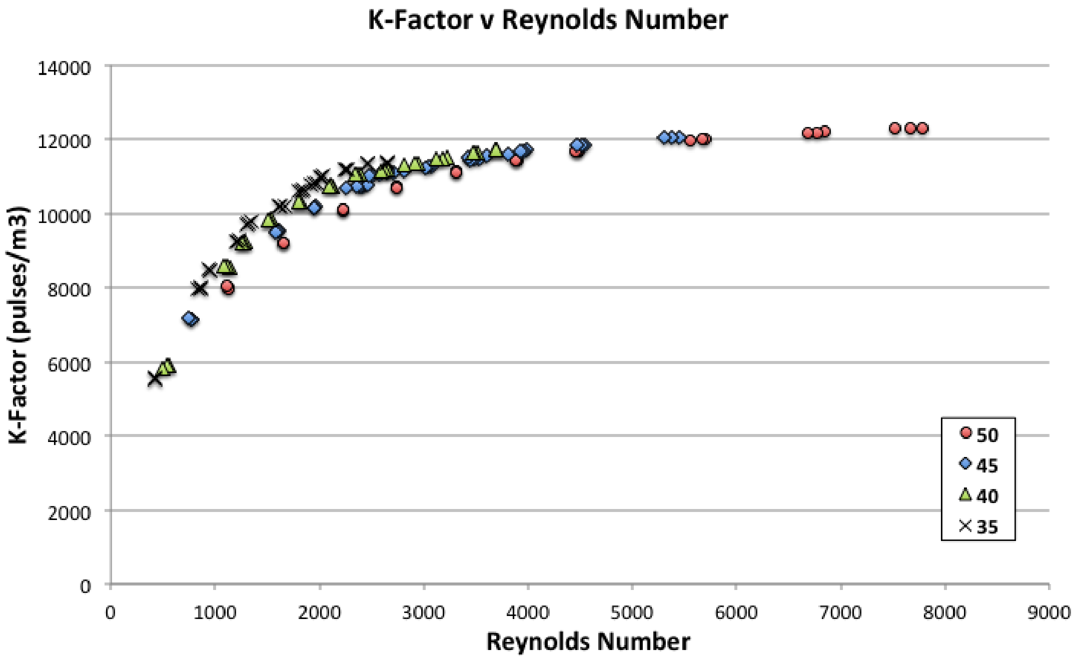

Figure 13: K-Factor v Reynolds number

The meter was a spare turbine meter previously used as a reference for the NEL water flow facilities. It had not been previously tested in higher viscosity fluids. **Figure 13** shows a dependence on both temperature and Reynolds number on the performance of the turbine meter.

For Reynolds number, it is clear if the operational Reynolds number is unknown then there is potential to introduce large errors into the measurement. Over the range of 1000 to 5000 Reynolds number there is nearly a 50% drop in K-Factor.

The measured pressure loss over a 1.2 m straight pipe ranged from 10 mbar to 110 mbar over the velocity range of 1.3 to 8.7 m/s. The pressure loss over the turbine meter was 25 to 350 mbar over the same range.

Applying the method for this meter was not as straight forward as the Coriolis meter. Although the K-Factor curve versus Reynolds number is smooth the pressure loss ratio curve versus Reynolds number is not. At transition, there is a point of inflection that matches the change between laminar and turbulent flow as found in the Moody diagram. **Figure 14** shows the pressure loss ratio versus Reynolds number.

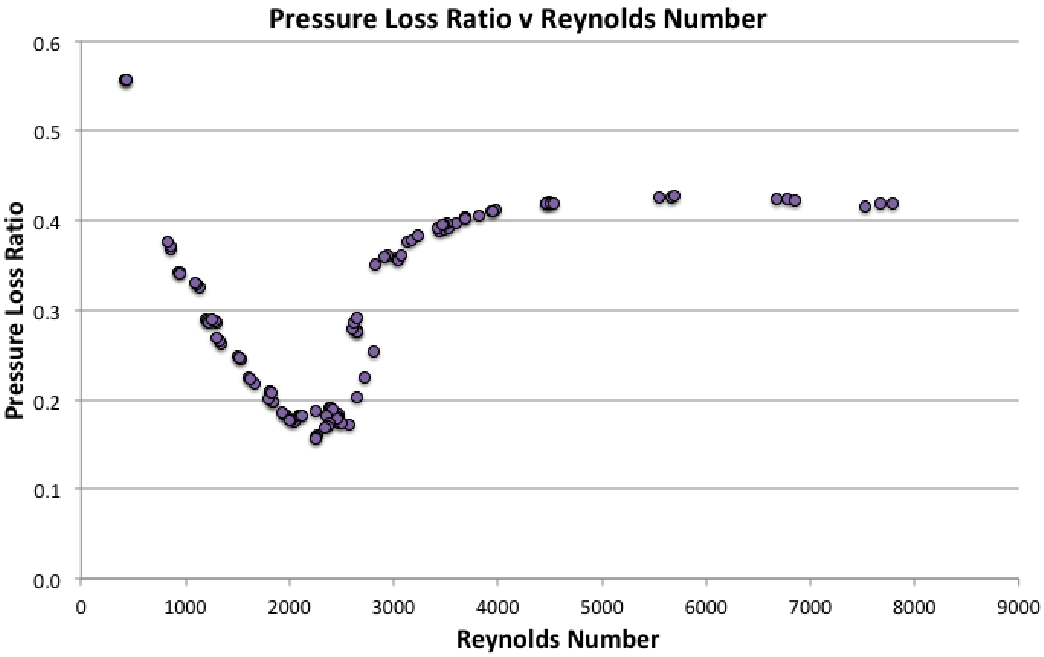

Figure 14: Pressure loss ratio v Reynolds number

This inflection makes the determination of Reynolds number challenging as there is sometimes two Reynolds numbers that would deliver the same pressure loss ratio. In fact, there are sometimes three Reynolds numbers as typically the pressure loss ratio decreases in turbulent flow at Reynolds number greater than those shown on **Figure 14**. In order to overcome the problem, both solutions are carried out with the end result chosen based on most probable answer.

Figure 15 shows the error in the calculated Reynolds number using this method and **Figure 16** shows the error in the turbine volumetric flowrate once corrected for Reynolds number.

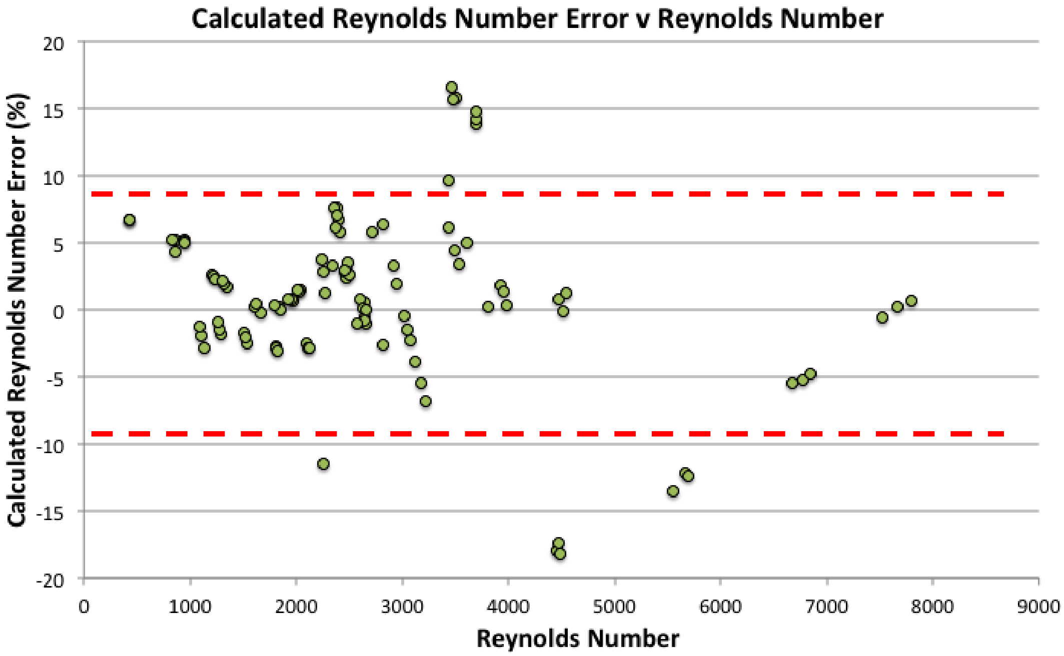

Figure 15: Calculated Reynolds number error v Reynolds number

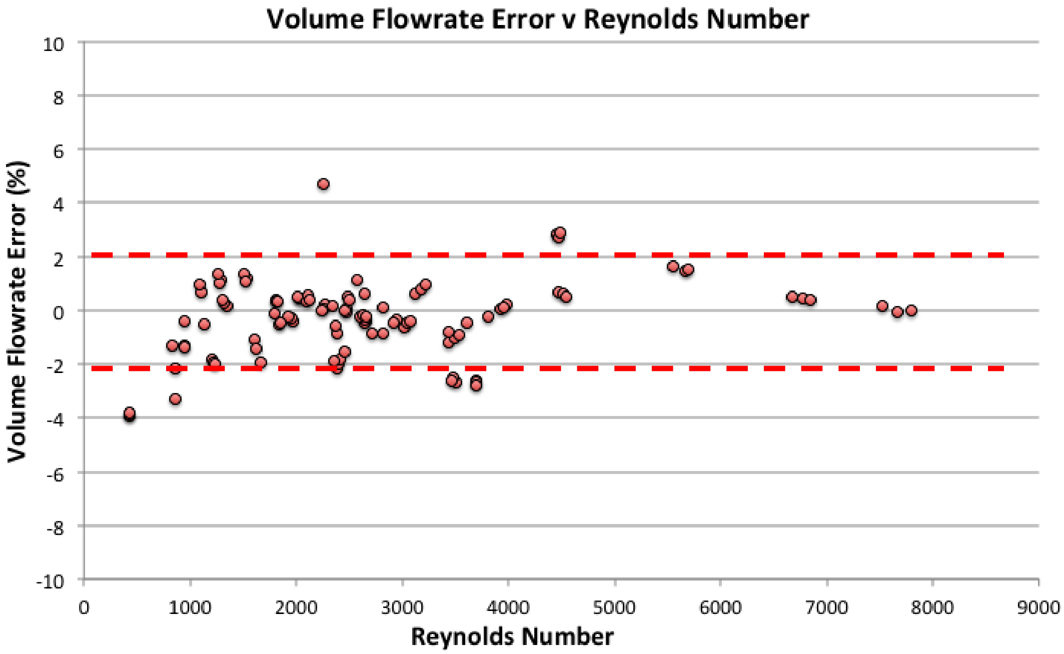

Figure 16: Corrected turbine meter volume flowrate v Reynolds number

For Reynolds number, the method predicts the majority of test points to within ± 10%. Although this is larger than the Coriolis meter and previously presented differential pressure meters it still provides a reasonable estimate. For instance, at a Reynolds number of 1000, the method predicts it to be within 900-1100, which is adequate to remove the majority of Reynolds number related errors.

For the turbine flowrate, using this calculated Reynolds number to base the K-Factor on allows the flowrate to be within 2%. Provided with a more accurate

Reynolds number estimation, as seen with other meters, would provide a better estimate of flowrate. In addition, this straight bladed turbine is not usually operated at these Reynolds numbers.

Figure 17 shows the calculated density using Equation 10 based on the corrected turbine meter volumetric flowrate. **Figure 18** shows the calculated volumetric flowrate from the differential pressure meter. As discussed previously, this is identical to the turbine meter measured flowrate as this is what the calculation of density is based on. Finally, **Figure 19** shows the calculated viscosity of the fluid using this method.

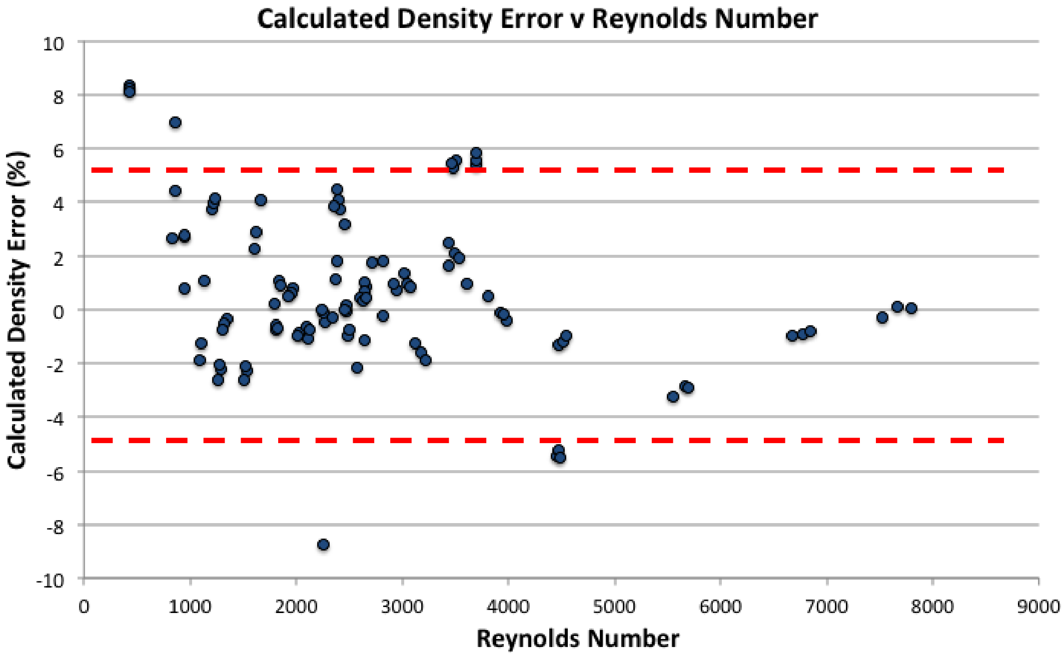

Figure 17: Calculated density error v Reynolds number

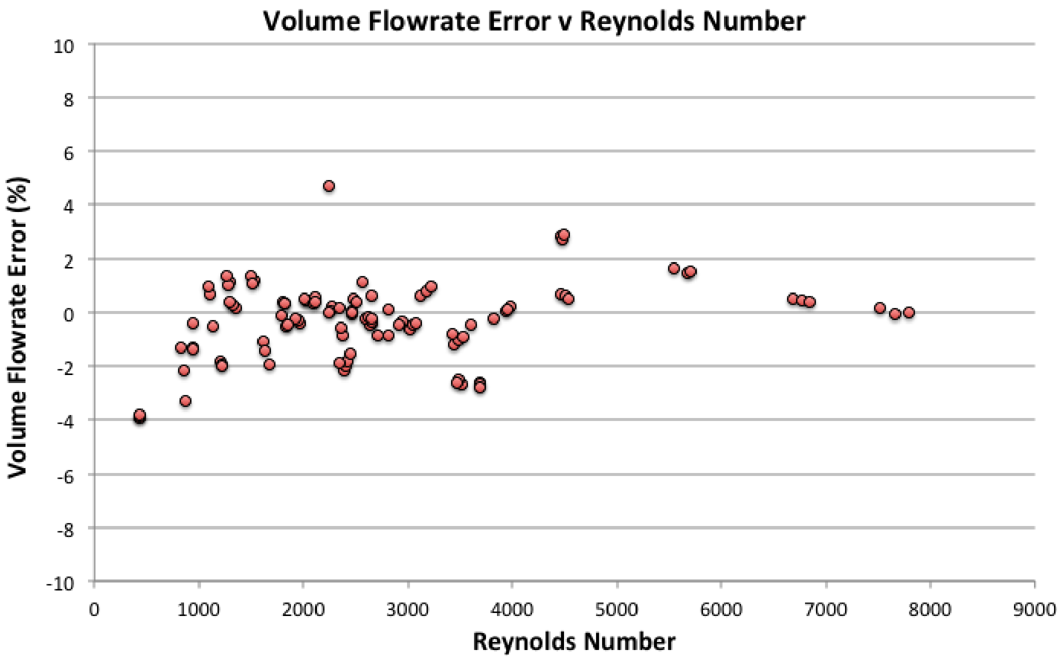

Figure 18: Calculated volume flowrate error of differential pressure meter v Reynolds number

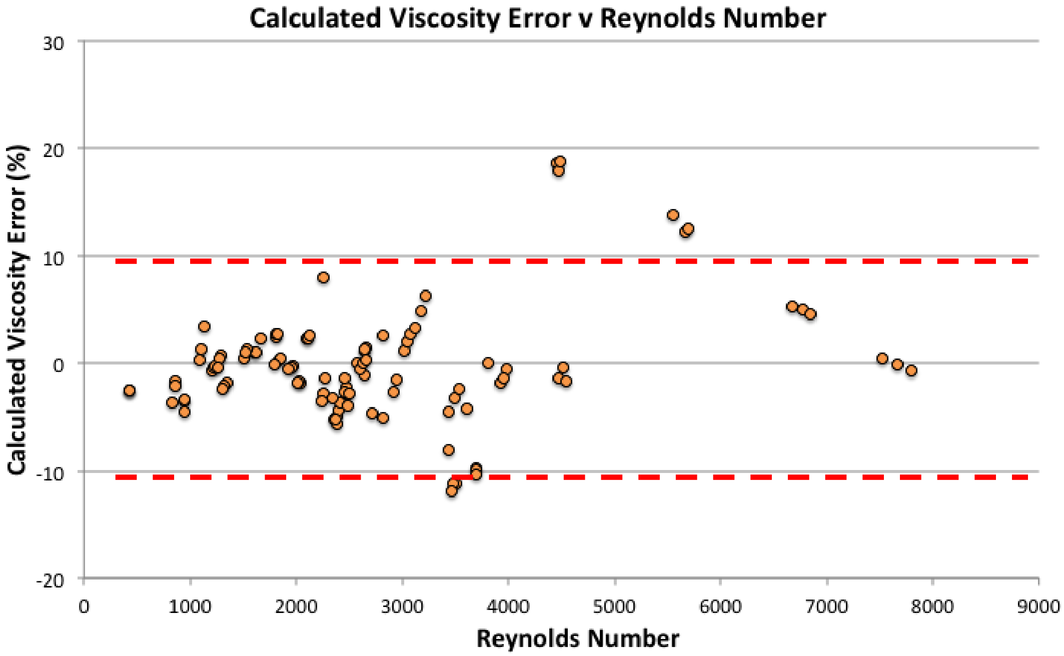

Figure 19: Calculated viscosity error v Reynolds number

The remaining errors in the calculation process are all larger than anticipated. This is primarily due to the poorer estimation of Reynolds number, and hence turbine flowrate and finally fluid density. There is a knock on effect with multiple calculation steps like this method.

The reason for the larger errors is due to the difficulty in characterising the relationship between pressure loss ratio and Reynolds number. This has been seen previously with Venturi meters where the larger beta devices exhibited a large change in pressure loss ratio during transition. However, smaller beta devices exhibited no such variation. It appears larger changes in geometry through a restriction helps to remove the effects of transitional flow and creates a smooth relationship between pressure loss ratio and Reynolds number.

4 UNCERTAINTY

As discussed, the measurement uncertainty of any measurement system is key for end user selection. There are a number of applications where the uncertainty is prescribed and must be adhered to but there are other general process measurement requirements where there is no limit to uncertainty and a low cost is more important.

With that in mind, a modular system offering flexibility should help to find a solution for the majority of applications. Whatever the technology, the measurement uncertainty can be calculated to see the impact of the measurements on the final parameters.

Specifically for this development, there are several methods of implementation that can be used. **TABLE 1** describes these implementations and provides estimates for the uncertainty in the measured or calculated process parameters. These estimates are for low Reynolds number applications and are based on a model created for a differential pressure meter. The numbers are a snapshot of estimated values for a Reynolds number of 1428 with input values from test data and some uncertainty input values manually manipulated to achieve the data below.

TABLE 1: Uncertainty estimates for measured parameters

Implementation Method	Flow	Density	Viscosity	Reynolds Number
2% meter only	2%	n/a	n/a	2.5%
2% meter using flowrate to calculate density	2%	4.2%	5.3%	2.5%
2% meter with densitometer	2%	0.1%	3.2%	2.5%
1% meter only	1%	n/a	n/a	2.5%
1% meter using flowrate to calculate density	1%	2.2%	3.5%	2.5%
1% meter with densitometer	1%	0.1%	2.7%	2.5%
0.5% meter only	0.5%	n/a	n/a	2.5%
0.5% meter using flowrate to calculate density	0.5%	1.4%	2.9%	2.5%
0.5% meter with densitometer	0.5%	0.1%	2.5%	2.5%
0.25% meter only	0.25%	n/a	n/a	2.5%
0.25% meter using flowrate to calculate density	0.25%	0.85%	2.7%	2.5%
0.25% meter with densitometer	0.25%	0.1%	2.5%	2.5%

The uncertainty in calculated Reynolds number tends to be lower in laminar flow than turbulent flow, which is why 2.5% was attainable in these calculations. To cover the full range of process conditions this will likely increase to around 5%.

The uncertainty in flowrate is determined by the uncertainty of the meter installed with four examples presented in **TABLE 1**. The density uncertainty is either given as 0.1% for density obtained from other means e.g. a dedicated densitometer or the calculated value. It is clear that the lower the flowrate uncertainty, the lower the calculated density uncertainty will be. This reaches a minimum of around 0.85% for this model where it cannot be improved any further.

The uncertainty in viscosity is large for systems with larger flowrate uncertainty but again starts to decrease as flowrate uncertainty improves. This reaches a minimum value of 2.5% i.e. the uncertainty in Reynolds number. The viscosity uncertainty will never be lower than the Reynolds number uncertainty.

From **TABLE 1**, it is clear that there are many different options available to implement this system and each have their advantages and disadvantages. There is a tendency for the options with the lower uncertainties to be more costly to implement. The balance of cost and measurement uncertainty will be the deciding factor during any implementation.

5 DISCUSSION

The theme running through this paper has been on reducing costs in measurement through better use of technology. This may be advancement in accuracy, better diagnostic capabilities or reducing the amount of equipment in use. All help move towards reducing the cost of ownership for the end user.

The example method presented is one making use of a frictional pressure loss upstream of an installed meter. The method offers a two-step process to improve measurement systems in low Reynolds number applications. Firstly, a generic Reynolds number correction method that will remove the effect of Reynolds number on measurement performance. Secondly, the ability to calculate physical properties of the flowing fluid instead of requiring separate measurement devices.

For the Reynolds number correction, the main advantage is calculating real-time Reynolds number without any prior knowledge of density or viscosity. In low Reynolds number applications, both physical properties are particularly important, as the sensitivity of the meter's performance index to Reynolds number is much larger than in conventional applications; where the Reynolds number is much higher ($Re>1x10^5$). Given this sensitivity, in the conventional method of calculating Reynolds number, any small errors in the values of density or viscosity will cause errors in calculated Reynolds number, which cause much larger errors in the applied performance index. However, acquiring the operational Reynolds number independently of physical properties means these errors will not be present.

One example of where this would be of benefit is in an oil-offloading terminal where many different types and qualities of fluid are offloaded and stored. A high accuracy measurement skid with onsite verification will typically perform the offloading measurement. Having a system in place that correctly determines Reynolds number as the fluid is flowing will improve the accuracy of the system and reduce the number of verification checks or proves required. Reducing the amount of time a prover loop is in operation has cost savings in itself.

The next step of the method presented requires a secondary flowrate or density input and allows the calculation of physical properties of the fluid. It makes use of this new situation where Reynolds number is already known. This part of the development is extremely flexible with any form of input being able to be used and having its associated uncertainty carry through to the uncertainty in the final calculated components. For instance, if a flowrate with ± 2% uncertainty is used, the uncertainty in density and viscosity may well be over 4 and 5% respectively. If using a flowrate with ± 0.25% uncertainty, the uncertainty in density and viscosity will be much reduced.

Of course, there will be different costs associated with the ± 2% or ± 0.25% flow estimates, which end users will have to decide upon. The best option for one may not be the case for another. A flexible approach helps meet the needs of a larger set of applications.

Using the second step of the development is not without limitations. Any errors in the calculated density and flowrate are linked to any errors in the additional measurement input used. Therefore, if that input goes into error for some reasons e.g. gas evolving in the system, then all of the measurements will be in error also.

In terms of physical measurements, the requirements are two differential pressure sensors and an intrusive meter. The intrusive meter will be sized appropriately for the application for both flowrate and pressure loss. This means that the measurement of pressure loss over the meter will be adequately large. In these experiments, the pressure loss was at least above 25 mbar – a common minimum range used.

The other differential pressure loss along a straight piece of pipe is a lot lower and needs to be sized to deliver a large enough differential pressure so that the uncertainty in this measured parameter does not become overly significant. In smaller pipe diameters, there is a larger pressure loss compared with the same velocity at larger pipe diameters. A minimum length of ten pipe diameters has been used previously but the longer the length the better the resolution of the measurement. This limitation will have repercussions for systems where the overall package length is limited or the pipe diameter is large.

This paper has covered the use of the system in high viscosity liquids only but there is potential for implementation in lighter oils or even gases. However, as the operational Reynolds number increases, there comes a point (fully turbulent flow) where friction factor becomes independent of Reynolds number and it becomes impossible to iterate to a solution. In fact, even before reaching fully turbulent flow the method accuracy for calculating Reynolds number will worsen. This is because the gradient of the relationship between friction factor and Reynolds number becomes shallow and the uncertainty becomes too large. In addition, there is a tendency for less viscous liquids to have lower density, which reduced the expected pressure loss again. A fact further compounded when the fluid changes to gas and density is sometimes a factor of ten or more lower still.

Regardless, even when a solution cannot be found for Reynolds number (and hence viscosity) there is still potential to calculate density of the fluid. Proof of concept in this application has not been completed but if successful it could offer a gas mass measurement, which could offer another solution for applications where gas composition is not required. The upstream length required will likely be significant however.

Lastly, as mentioned previously, there is potential to turn the system into a comparative diagnostics package. This is where the installed meter produces a measured flowrate and the differential pressure measurements also allow for a secondary flowrate calculation. The caveat is that a separate density measurement is included that is totally extrinsic from the installed meter as only then does the differential pressure flowrate calculation become different from the installed meter. **Figure 20** shows an example of the Reynolds number corrected mass flowrate from the Coriolis meters in section 3.2 and the corresponding differential pressure meter mass flowrate when the Coriolis density was used as the input for density.

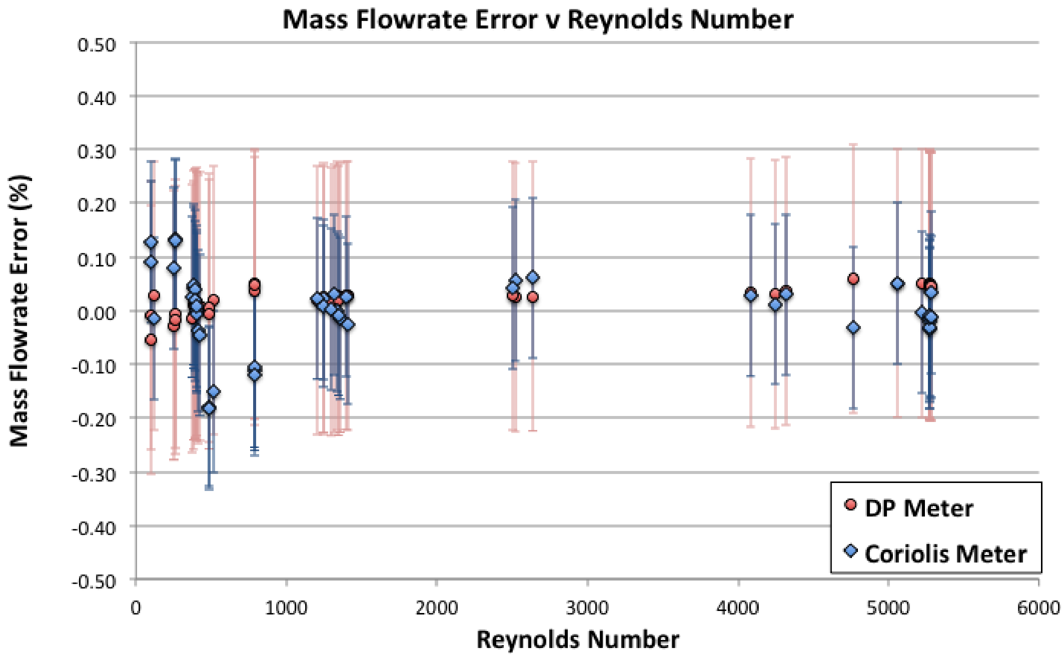

Figure 20: Example of comparative diagnostics

Figure 20 shows the mass flowrates from each meter in agreement within suggested uncertainties of 0.15% for the Coriolis and 0.25% for the differential pressure meter. Ideally, the uncertainties would be smaller to pick up on smaller changes. Any factor that affects performance should affect each meter to varying degrees, which would be found through the comparison.

It is important to point out that some of the concepts presented are not new and have been implemented by many companies with varying levels of success. In particular, the use of two meters (usually a mass and volume meter) to calculate density of the fluid and the use of two or more meters as a diagnostic comparison. What is new is the application of these concepts with the new equation for friction factor, which allows the calculations to be done slightly differently, and with less knowledge about the fluid to begin with. The concepts are suggested here as methods of helping to reduce on going costs found in measurement systems and help reduce cost of ownership.

6 CONCLUSIONS

This paper has presented follow on work involving the advances in a flow measurement method including a frictional pressure loss. The method has been adapted to work with Coriolis and turbine flowmeters.

This adaptation has some advantage over the previously presented differential pressure work; namely the reduction of equipment and improvement in accuracy for the measured and calculated process parameters. In particular, with the Coriolis meter, which offers multiple outputs itself, there are two methods that can be implemented. The second method of using the measured Coriolis density in the calculation of differential pressure flow offers a separate flowrate calculation that can be used for diagnostics purposes.

7 NOTATION

D	Pipe diameter
d	Throat diameter
C_d	Discharge Coefficient
L	Length
ΔP	Differential Pressure
Q	Flowrate
Re	Reynolds number
r	Pipe relative roughness
u	Velocity

β	Ratio of throat to pipe diameter
ε	Expansibility
λ	Friction factor
μ	Dynamic viscosity
ρ	Density
	Subscripts
f	Frictional
1	Position 1
v	Volumetric
m	Mass