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MEASUREMENT OF FLOW IN VISCOUS FLUIDS USING A HELICAL BLADE TURBINE

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1 INTRODUCTION

It is now widely accepted that world oil reserves are split approximately into 70% high-viscosity and 30% (low-viscosity) conventional light oils. Exploitation of these viscous deposits is growing rapidly, buoyed by occasional high oil prices and an increasing demand for security of energy supply.

As such, there exists a growing requirement for accurate flow measurement of heavy crude oils and other viscous products. Unfortunately, the performance of conventional flowmeters when applied to viscous fluids[1] remains relatively poorly known. However, a number of technical challenges are immediately identifiable. These include the higher viscous friction of the fluid being metered, the increased pressure losses incurred across internal bends and restrictions, the possibility of extreme or varying velocity profiles, and the increased susceptibility of viscous liquids to entrain secondary components such as solids or gas. It is reasonable to predict that different metering devices will be affected by these phenomena in different ways, but to date the most appropriate technologies for viscous flow measurement are not yet well defined.

One technology that is believed to be suitable for high viscosity flow measurement is the helical blade turbine. Helical blade turbine flowmeters claim to have a low sensitivity to viscosity changes, low pressure drop and a relatively wide turndown ratio. The repeatability for these meters is stated as being in the region of ±0.02%, but to date there has been little independent and verifiable data published. This follows partly from the scarcity of suitable test facilities capable of providing viscous flow in combination with accurate and traceable reference instrumentation.

To improve this situation, NEL has completed an investigative programme into the performance of a helical blade turbine flowmeter across a range of viscosity conditions. This paper reports on the response of a helical blade turbine flowmeter when operated from 2 – 500 cSt at the UK National Standards Oil Flow Facility at NEL in Glasgow, Scotland.

2 FLOW MEASUREMENT CHALLENGES

Flow measurement of ‘medium’ and ‘heavy’ crude oils present additional technical challenges compared to ‘light’ crude oils due to their greater viscous friction. Challenges such as irregular flow regimes and pressure drop will be discussed in more detail in the sections below.

[1] For the purpose of this paper, ‘high’ viscosity in relation to hydrocarbon liquids, is taken as a kinematic viscosity > 50 cSt.

2.1 Characteristics of Viscous Fluids

2.1.1 Flow Regime

The level of force exerted due to viscous friction can be characterised by its viscosity coefficient. The absolute viscosity of a fluid can be expressed in centi-Poise (cP). The higher the value of absolute viscosity, the greater the frictional viscous forces on the pipe wall. As an example, the viscosities of some common fluids are listed in Table 1.

Table 1 – Fluid viscosity

Fluid Type	Viscosity at 20 ^{O}C (cP)
Water	1
Engine Oil	100
Gear Oil	1000
Honey	10000

Another often quoted definition for viscosity is the kinematic viscosity. It is defined as the ratio of the fluid's dynamic viscosity to its density and is generally quoted in centi-Stokes (cSt). The SI units are m^2/s and the unit conversion is 1 m^2/s = 1 x 10^6 cSt.

For most liquids, an increase in temperature normally results in a decrease in fluid viscosity. The decline in viscosity with increasing temperature is generally far greater for highly viscous fluids and can pose several problems. Figure 1 displays the kinematic viscosity of two NEL test fluids, one light and one heavy, plotted against fluid temperature.

Problems can arise in the flow measurement of viscous fluids when small fluctuations in temperature result in a significant change in the fluid viscosity. If the flowmeter has been calibrated at a specific viscosity for its application, any temperature and thus viscosity fluctuation could potentially have a notable effect on the flow measurement.

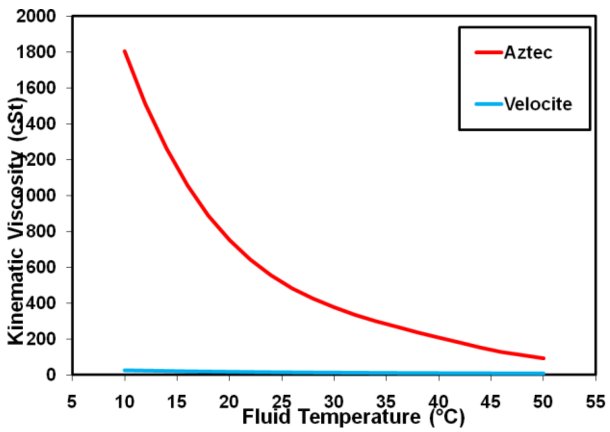


Figure 1 – NEL test fluid viscosities

In highly viscous fluids there can be distinguishable variations in the measured temperature due to thermal gradients within the flow path. Thermal gradients are often present in laminar flow due to the parabolic velocity profile that occurs. As there is no mixing taking place between the layers of fluid, the fluid at the centre of the pipe will be at a different temperature than the fluid at the pipe wall. These thermal gradients can make it problematic to obtain a suitably representative mean fluid temperature. This increases the uncertainty of any temperature based correction applied by the device.

The velocity profile of the fluid is also considerably altered by changes in the fluid viscosity. The influence that fluid viscosity exerts on the velocity profile is best defined using the Reynolds number (Re), the dimensionless ratio of inertial forces to viscous forces in a flowing fluid.

Reynolds Number can be written as:

$$\mathrm{Re} = \frac{U\ D}{\nu} \tag{1}$$

where:

U	=	Average fluid velocity [m/s]	D	=	Pipe diameter [m]
υ	=	Kinematic Viscosity [m²/s]			

A flowing fluid travels in one of three different flow regimes. Low viscosity fluids travelling at moderate velocities would normally have a high Reynolds number (greater than ~10,000), leading to turbulent flow (Figure 2a). In this regime dynamic forces dominate and the motion is parallel to the pipe axis with mixing occurring between the different layers. When the Reynolds number is low (less than ~2,000) the flow is laminar (Figure 2b). In this regime viscous forces dominate and there is no mixing between the layers. The regime between laminar and turbulent flow is described as ‘transitional’ and can be extremely unpredictable. The flow quickly switches back and forth between laminar and turbulent behaviour and can cause significant flow measurement challenges.

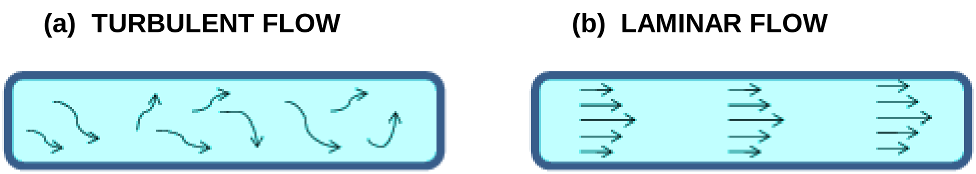


Figure 2 (a) turbulent and (b) laminar flow conditions.

The flow regime has a direct impact on the shape of the flow profile within the pipe. The velocity profile defines how quickly the liquid is travelling at various points across the cross section of the pipe. Fully developed velocity profiles for laminar and turbulent flow are shown in Figure 3.

In laminar flow, viscous forces dominate causing substantial friction against the pipe wall and the fluid. This results in drag between the layers of the fluid with the fluid velocity gradually increasing from the pipe wall to the centre. The maximum velocity at the centre of the pipe can be approximately twice the average velocity of the flow which results in a velocity profile that is parabolic in shape.

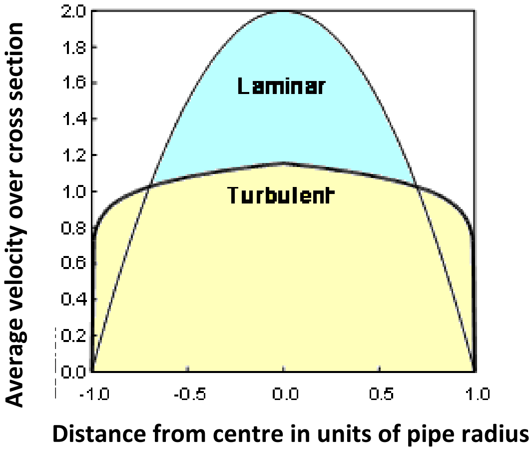


Figure 3 – Laminar and turbulent velocity profiles.

In turbulent flow, the mixing action caused by the dynamic forces breaks up any gradual transfer of drag from the pipe wall. This results in a well-mixed flow with a relatively flat velocity profile.

The central axis of fully developed turbulent flow normally has a value of 1.1 to 1.3 times the average flow velocity.

2.1.2 Pressure Drop

Pressure loss is a critical consideration in high viscosity fluids applications, since frictional losses increase with increasing viscosity. There is therefore an incentive to minimise flowmeter pressure drop to avoid excess pumping power requirement. If the differential pressure across a flowmeter is sufficiently high it could potentially lead to internal (and unmeasured) leakage of fluid through the device. In extreme cases its mechanical integrity might even be compromised.

Turbine flowmeters are known to have a larger pressure drop than many other conventional flowmeters due to the multiple blades situated within the device. To avoid a large pressure drop, some users might select a turbine flowmeter that has a larger bore than the line size. For example, a 6 - inch (152.4 mm) flowmeter for a 4 - inch (101.6 mm) line size.

More likely, especially in heavy oil applications, is that the pipe size is increased to reduce pressure loss and velocity in the main pipeline. The pipe size will then have to be reduced to ensure the flowmeter is within its operating range. Operating too far down the operating range can result in a higher flow measurement uncertainty through poor linearity and decreased repeatability. However, local pressure drops will then dominate with potential risk of flashing or cavitation.

2.2 Scope of Current Work

The effect that increasing fluid viscosity has on the current generation of liquid flowmeters (Coriolis and ultrasonic) has already been reported [1]. However the effect of high viscosity fluids on helical blade turbine flowmeters has not yet been defined with independent and verifiable test data. This follows partly from the scarcity of suitable test facilities capable of providing viscous flow in combination with accurate and traceable reference instrumentation.

The scope of work for the test programme was to explore the performance of a helical blade turbine across a range of liquid viscosities (2 - 500 cSt). The investigations reported in this paper focus solely on the performance of one 4-inch helical blade turbine flowmeter. Such flowmeters are generally regarded as being suitable for flow measurement of high viscosity fluids.

3 TEST METER

3.1 Helical Blade Turbine

Turbine flowmeters are still one of the most commonly used flowmeters for low uncertainty measurement of high value liquids [2]. For low viscosity oils, conventional turbine flowmeters remain predominant. However, studies [3] have shown that conventional turbines are not suitable for metering oils with viscosities greater than about 30 cSt. For higher viscosity fluids, helical blade turbine meters are believed to be more appropriate (Figure 4). Helical blade turbine flowmeters are manufactured by several vendors, including SmithMeter™, M & T and Faure Herman.

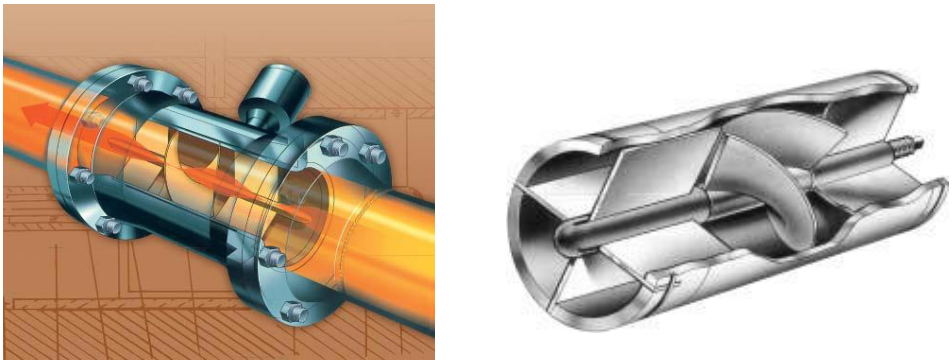
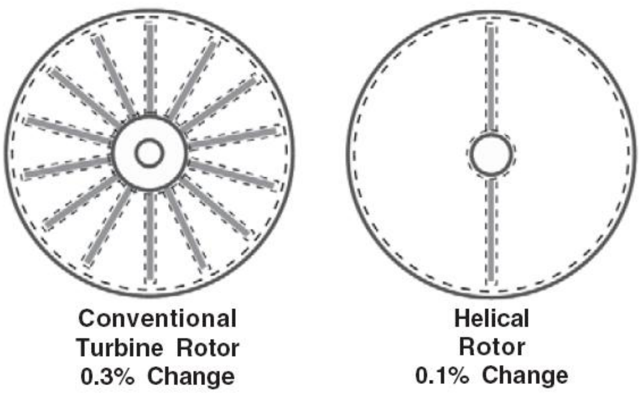


Figure 4 – Example of Helical Blade Turbine Meter (left) [4] and Removable Cartridge with Rotor (right)

Helical blade turbine flowmeters have two blades, twisted to minimise the angle of incidence to the flow. The blades are generally mounted in a cartridge, as shown in Figure 4. This equalises the pressure across the metering tube, preventing problems with expansion, in much the same way as a double casing works in a positive displacement (PD) meter.

Manufacturers claim a typical repeatability of ±0.02% and a linearity of ±0.15%, when a meter is calibrated with a fluid of the same viscosity as the operating fluid. However, changes in fluid viscosity have the effect of altering the thickness of the fluid boundary layer on the walls of turbine meters' cartridge and on the blade surfaces. This affects the lift forces that drive the turbine blades and hence their rate of rotation. Consequently conventional turbines can be quite sensitive to changes in fluid viscosity.

As helical blade turbines have fewer blades, which are more aligned with the flow, the effect of boundary layer growth and hence their sensitivity to viscosity changes is claimed to be reduced, as illustrated in Figure 5.



As they are less sensitive to viscosity effects, it is the helical blade turbine designs that tend to be used to meter higher viscosity fluids. In fact, some helical blade turbine manufacturers even claim accurate performance in oils with viscosities as high as 1000 cSt.

Figure 5 – Illustration of the Change in Cross-sectional Area Caused by a 0.0254 mm Boundary Layer on Conventional and Helical Blade Turbine Meters [5]

One downside of operating at increasingly high viscosities is that the turndown ratio of the flowmeter generally decreases, as illustrated in the example of Figure 6.

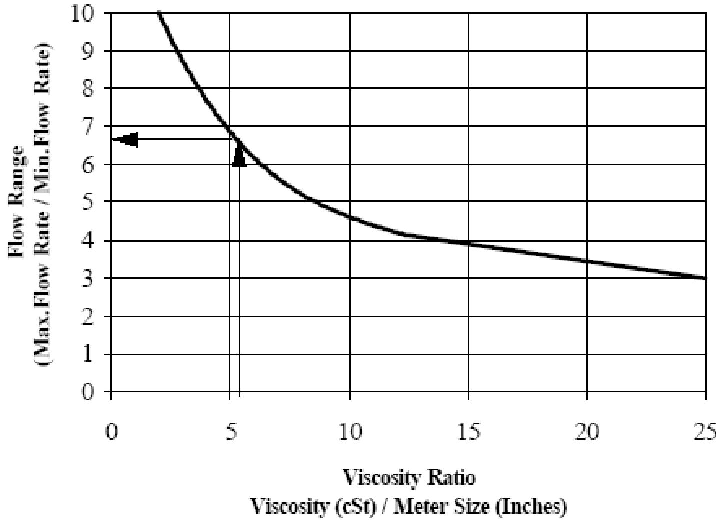


Figure 6 – Flow Range Achievable at ±0.15% Linearity for a Leading Commercial Helical Blade Turbine Meter, as a Function of Liquid Viscosity [4]

The performance of helical blade turbine flowmeters is not specifically covered in either API MPMS Chapter 5.3 [6] or British Standard 6169-2 [7]. However a revision was made to ISO standard 2715 in May 2002 to include details of the performance of helical blade turbines flowmeters. Unfortunately, this ISO standard was time barred and is not publicly available. The data published in this paper could possibly be included in a future revision of ISO 2715.

3.2 Test Meter Description

The flowmeter evaluated in this test programme was a 4 – inch (101.6 mm) helical blade turbine. This project was not structured as an evaluation of any particular manufacturer or flowmeter model, but rather as a generic evaluation of some of the effects of high viscosity on helical blade turbine technology. As such, the manufacturer of the flowmeter evaluated in this programme will not be named.

The specification of the flowmeter evaluated is detailed in Table 2.

Table 2 – Helical Blade Turbine Specification

Parameter	Specification
Flow Range	20 – 200 m^3/hr
K-factor	2050 m^3/hr
Claimed Uncertainty	± 0.15 %
Claimed Repeatability	± 0.02 %
Viscosity Range	0.1 – 350[2] cSt

[2] 350 cSt is the standard quoted upper viscosity limit for the helical blade turbine tested. However, the flowmeter manufacturer claims the device will perform up to 1000 cSt.

4 EXPERIMENTAL PROGRAMME

4.1 Oil Flow Facility

The experimental programme was completed in 2011 at the UK National Standards Oil Flow Facility, located at NEL in Glasgow, Scotland. The facility 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 10” (12.7 – 254 mm), and can operate at line pressures up to 10 bar. Test fluids can be delivered at flowrates up to 720 m^3/hr.

Six test fluids are available in this facility – Kerosene, Gas Oil, Velocite, Primol, Siptech and Aztec – covering liquid viscosities from 2 to 1500 cSt. Figure 7 displays the kinematic viscosity of NEL’s test fluids for the Oil Flow Facility in 2011.

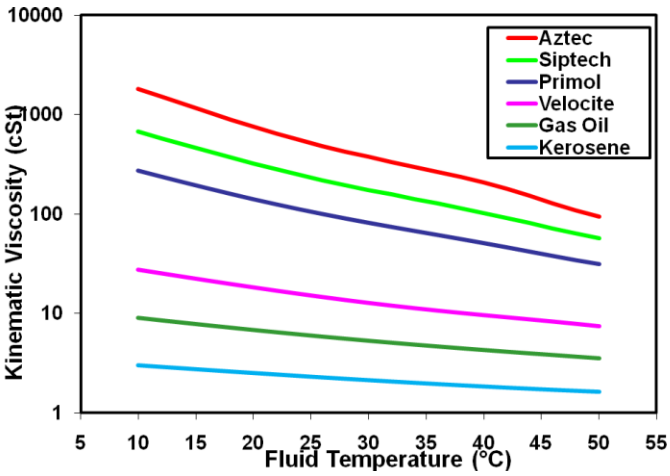


Figure 7 – Kin. Viscosity of NEL test fluids.

Figure 8 shows a schematic diagram of the flow circuits. The oil for each circuit is drawn from a 30 m^3 supply tank, from where it is discharged to the test lines. A conditioning circuit, linked to each tank, maintains the oil temperature to within ± 0.5 ºC of a pre-selected value (itself set in the range 10 – 50 ºC).

The main test line can accommodate up to 30 m of horizontal straight lengths or alternative configurations as required. The test line can also accommodate 1 metre long sections of Perspex pipe work to enable flow visualisation. At the outlet of each test section, a manifold directs the test 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. The flow lines share a common primary standard weighbridge system consisting of four separate weigh tanks 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) to ISO 17025.

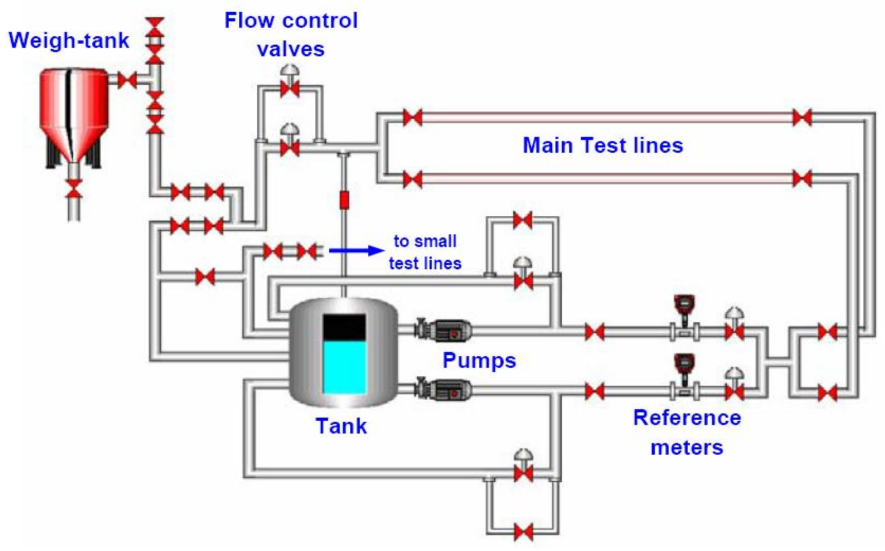


Figure 8 Schematic diagram of the NEL oil flow test facility.

4.2 Reference System

For "primary" calibrations, a gravimetric "standing-start-and-finish" method is used to determine the quantity of fluid (volume or mass) which has passed through the flowmeter under test and into the selected weigh tank. The gravimetric weigh tanks constitute the primary reference standard of the NEL oil flow facility.

Using the above technique, the overall uncertainty in the quantity of fluid passed, expressed at the 95% confidence limit 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 typical uncertainties in the quantity of fluid passed of the order of ± 0.08 % (k = 2). This applies to oils with a kinematic viscosity between 2 – 30 cSt.

In the evaluation programme for the low viscosity data (2 – 18.4 cSt), the oil flow facility was operated in 'standing-start-and-finish' mode and the test meter compared against the primary gravimetric reference system.

In the evaluation programme for the high viscosity data (80 – 500 cSt), the oil flow facility was operated in 're-circulation' mode and the test meter compared against secondary reference standards – in this case a pre-calibrated volumetric device.

The reference meter used in the present test programme consisted of one 8-inch rotating-vane Positive Displacement device (Smith Meters™), manufactured by FMC Technologies. The "K-factor" for this type of PD meter can be considered to be a function of three main parameters: the volumetric flowrate (Q), the liquid viscosity (ν) and the fluid temperature (T).

The PD meter was calibrated (as a function of flowrate only) for the fluid temperature and fluid type detailed in the test matrix. This provided the most accurate reference for testing and produced a K-factor curve of the form:

$$K_{F,T} = f_{F,T}(Q) \tag{2}$$

where F and T denote the fluid type or test temperature respectively. The resultant uncertainty of the PD meters in service was of the order of ± 0.15% at the 95% confidence level.

4.3 Test Matrix

To investigate the sensitivity of the helical blade turbine flowmeter to elevated fluid viscosity, a series of tests were made on the flowmeter, at a controlled and monitored rate.

The test installation was based around a standard pipeline run of 4-inch (101.6 mm) nominal bore. Tests were conducted at flowrates in the range 5.6 to 55 l/s (10:1 turndown); using Kerosene, Gas Oil, Velocite and Siptech test fluids, covering a fluid kinematic viscosity range of 2.2 – 500 cSt.

To enable the effects of elevated viscosity to be evaluated, the nominal test matrix of Table 3 was proposed.

Table 3 – Test Matrix

Fluid	Temperature [°C]	Density [kg.m^{-3}]	Kin. Viscosity [cSt]
Kerosene	20	780	2.2
Gas Oil	20	806	6.8
Gas Oil	12	812	9
Velocite	20	824	18.4
Siptech	43	834	80
Siptech	27	851	200
Siptech	13.5	856	500

For evaluation purposes, the test meter was horizontally mounted in a discrete skid or 'package' based around straight pipe runs of 4-inch (101.6 mm) nominal bore. The package exceeded the manufacturer's recommended upstream and downstream straight pipe lengths of 10D and 5D respectively. An example of the test package is shown in Figure 9.

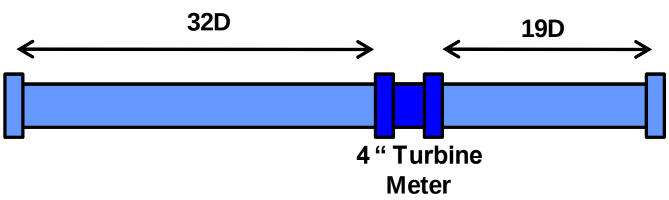


Figure 9 Example of the test package used to evaluate the helical blade turbine flowmeter.

5 TEST RESULTS

The test programme was completed in 2011 independently by NEL. The flowmeter manufacturer was not consulted or involved in the testing.

It should be noted that the test results include high viscosity flow measurement. This remains a problematic area for flow measurement technologies and improving the uncertainty in this area requires further investigation. The device was also tested above the manufacturer’s standard quoted upper viscosity level of 350 cSt. However, these tests were completed last and as such had no effect on the performance of the meter at lower fluid viscosities.

5.1 Volumetric Flowrate Results

The evaluation programme performed on the helical blade turbine included no artificial flow conditioning within the test line, but incorporated at least 32D upstream and 19D downstream of straight pipe. The meter was operated with no adjustments made for any potential influences of high viscosity, low Reynolds number or temperature effects.

Figure 10 displays the response of the helical blade turbine meter when operated at a range of low kinematic viscosities (< 20 cSt). The K – factors are displayed with respect to individual fluid viscosities and are plotted against the reference volumetric flowrate.

For most of the low viscosity test data, altering the fluid viscosity appears to have little effect on the response of the flowmeter. Above 15 l/s, the effect of viscosity isn’t notable and the K – factors for the four different viscosities appear linear and mostly overlap.

However at low flowrates, the K – factor curves differ notably in shape. Below 15 l/s, the four different fluid viscosities (2, 6.8, 9 and 18.4 cSt denoted by red, yellow, green and blue markers respectively) produce an increased spread in K – factor. However this might not be viscosity effects but could be a result of the turndown of the device or even Reynolds number effects. This will be discussed in Section 5.2.

Figure 11 displays the K – factor results for both the low and high viscosity data. The K – factors for the 80 cSt, 200 cSt and 500 cSt data, denoted by purple, pink and orange markers respectively, all display a relationship with increasing viscosity. As the fluid viscosity increases, the number of pulses and thus the K – factor of the flowmeter decreases. This means that at similar fluid velocities the helical blade is rotating slower with higher viscosity fluids.

There is also the possibility that there are temperature effects occurring on the flowmeter, since the low and high viscosity data were obtained at different temperatures.

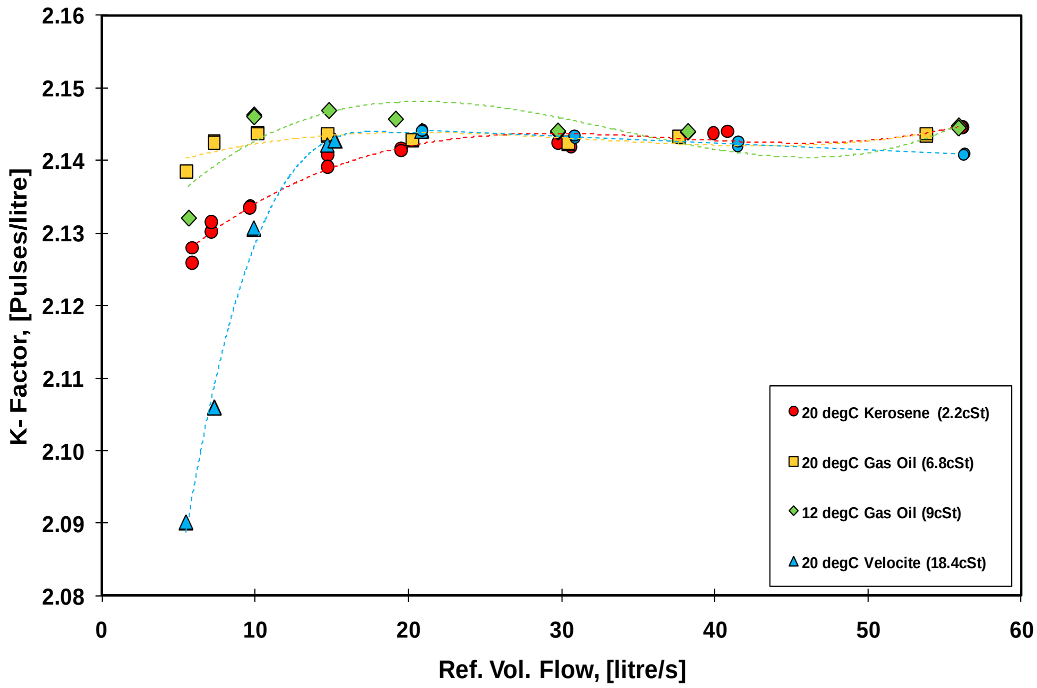


Figure 10 K – factors recorded for the helical blade turbine when operated at a range of low kinematic viscosities (< 20 cSt).

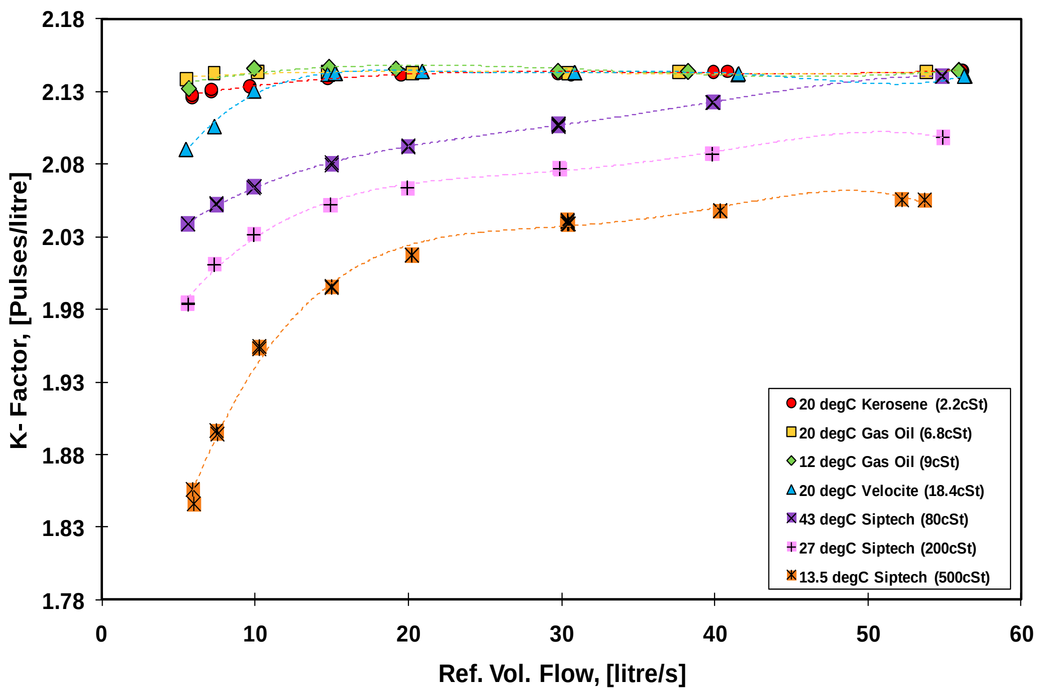


Figure 11 K – factors recorded for the helical blade turbine when operated at both high and low kinematic viscosities.

A question that might be asked is how well does a calibration transfer if the fluid viscosity changes from one value to another? As mentioned previously, small fluctuations in temperature can result in a significant change in the fluid viscosity in highly viscous fluids.

Figure 12 shows the results of reanalysing the low viscosity data using the K – factor for the **9 cSt fluid**. A third order polynomial curve fit was applied through the 9 cSt data and then used to calculate the resulting meter output and thus the volumetric error (deviation from reference) for the test data recorded at other fluid viscosities.

The majority of the volumetric flow errors for the 2 cSt, 6.8 cSt, 9 cSt and 18.4 cSt data, denoted by red, yellow, green and blue markers respectively, are all within ±0.5 %. The only outliers are for the 18.4 cSt data at flowrates below 10 l/s.

From this limited data set, it appears that there may be potential for calibrating a helical blade turbine at the mid viscosity of its application (i.e 9 cSt for a 2 – 18.4 cSt application), and then applying that calibration with confidence across the viscosity range; 95 % of the test data from 2 – 18.4 cSt were within ±0.5 %.

Figure 13 shows the results of reanalysing both the low and high viscosity data using the K – factor for the **9 cSt fluid**. The volumetric flow errors for the 80 cSt, 200 cSt and 500 cSt data, denoted by purple, pink and orange markers respectively, all display a large under-reading of the volumetric flow. Indeed, the under-reading increases with increasing fluid viscosity and, as expected, resembles the shape of the K – factor curves for the high viscosity test data.

From this limited data set, it would appear that calibrating at low viscosity and then using the device in a high viscosity application would not be appropriate. For almost the entire high viscosity test data (80 – 500 cSt), the volumetric flow errors are greater than -2 %.

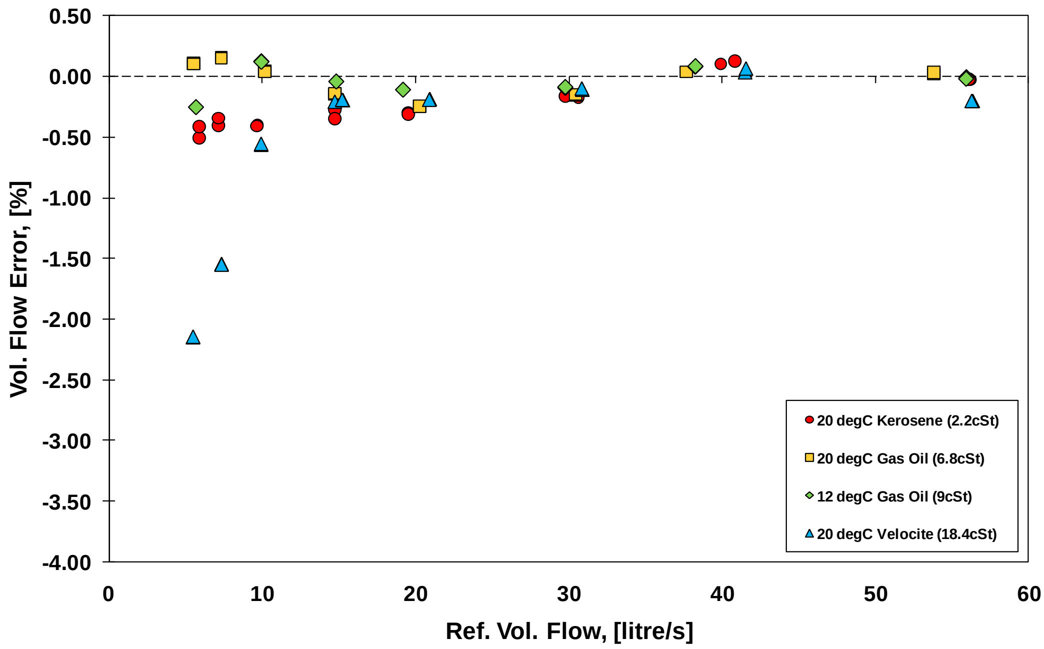


Figure 12 Liquid volume flow error recorded for the helical blade turbine when operated at a range of low kinematic viscosities (< 20 cSt). All of the test data was analysed using the K – factor recorded at **9 cSt** to assess the effects of changing viscosity on meter performance.

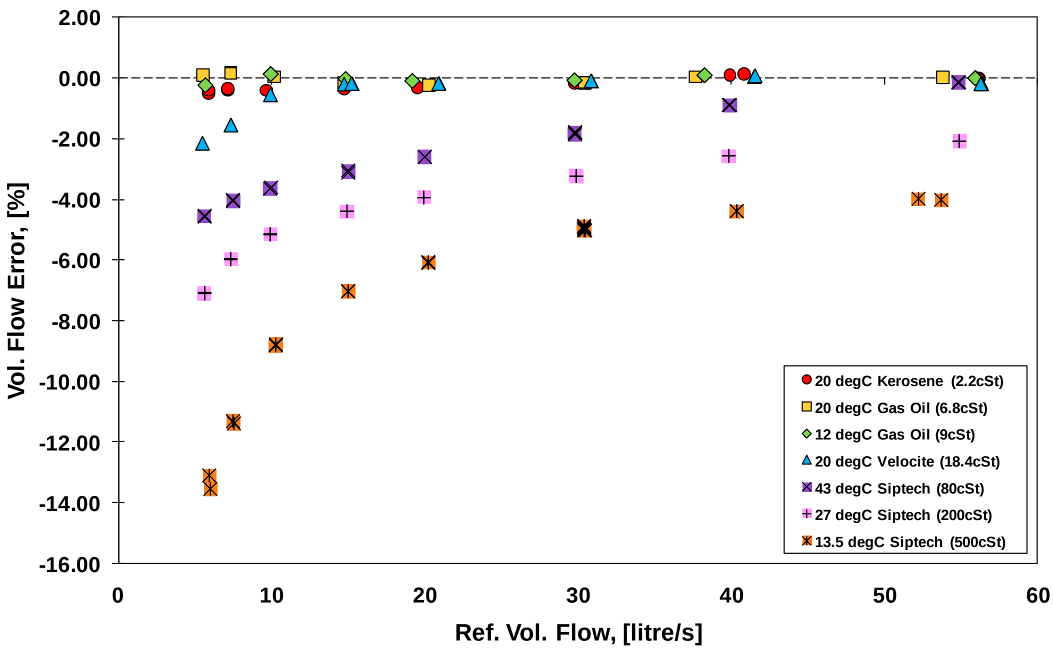


Figure 13 Liquid volume flow error recorded for the helical blade turbine when operated at both high and low kinematic viscosities. All of the test data was analysed using the K – factor recorded at **9 cSt** to assess the effects of changing viscosity on meter performance.

5.2 Reynolds Number Results

The results displayed in Figure 11 revealed that at high fluid viscosities (80 – 500 cSt) there is a notable decrease in K – factor. The decrease in K – factor appears consistent across the flow range and displays a notable trend with increasing fluid viscosity. To understand this trend it is worthwhile plotting the entire data against pipe Reynolds number (Figure 14).

The test data now appears to displays a notable trend with decreasing pipe Reynolds number. At Reynolds number below 10000, the K – factor of the helical blade turbine begins to substantially decrease. This deterioration suggests that there might be a shift in the response of the helical blades at low Reynolds numbers. In highly viscous fluids, it is possible to attain low Reynolds numbers with a moderate flow velocity relative to the fluid properties. Thus the effects observed cannot solely be attributed to low fluid velocity.

The maximum Reynolds number that laminar flow can theoretically occur is 10000. Typically between Reynolds number ranges of 2000 – 10000, transitional flow occurs. However the laminar-turbulent transitional region is facility dependent and can be affected by a mixture of variables, such as pipe roughness, pipe incline and upstream pipeline geometry. As the Reynolds number decreases to laminar flow, the parabolic profile of the fluid increases. It appears the change in flow profile that occurs from the transition from turbulent flow (Re > 10000) to transitional/laminar flow has caused the response of the turbine meter to decrease with decreasing Reynolds number.

The results in Figure 14 have been plotted in terms of viscosity and it can be seen that the decrease in K – factor at low Reynolds number is not solely a function of fluid viscosity or velocity but is in fact a result of flow profile. The overlap in K – factor for a similar Reynolds number but different fluid viscosity and velocity give credence to this argument.

The lowest viscosity data at 2 cSt, denoted by red markers, appears to show a slight decrease in the flowmeter’s K – factor at a Reynolds number range of 20000 – 80000. This trend was not overly noticeable in Figure 9. It is possible that this is a result of slippage between the turbine blades at such a low fluid viscosity.

The Reynolds number trend exhibited in Figure 14 suggests that there might be the possibility of calibrating the device in a non standard manner. One possibility might be to predict the K – factor using the Reynolds number which would be attained using details of the fluid properties.

This would be achieved by firstly calibrating the helical blade turbine meter against Reynolds number and then, using details of the fluid properties manually inserted into the flow computer, use a ‘look-up table system’ to predict the K – factor. This might mean that the device would not require calibration at the service fluid viscosity but instead would only require calibration at the service Reynolds number range.

The test results for this theory have not been reported in this paper.

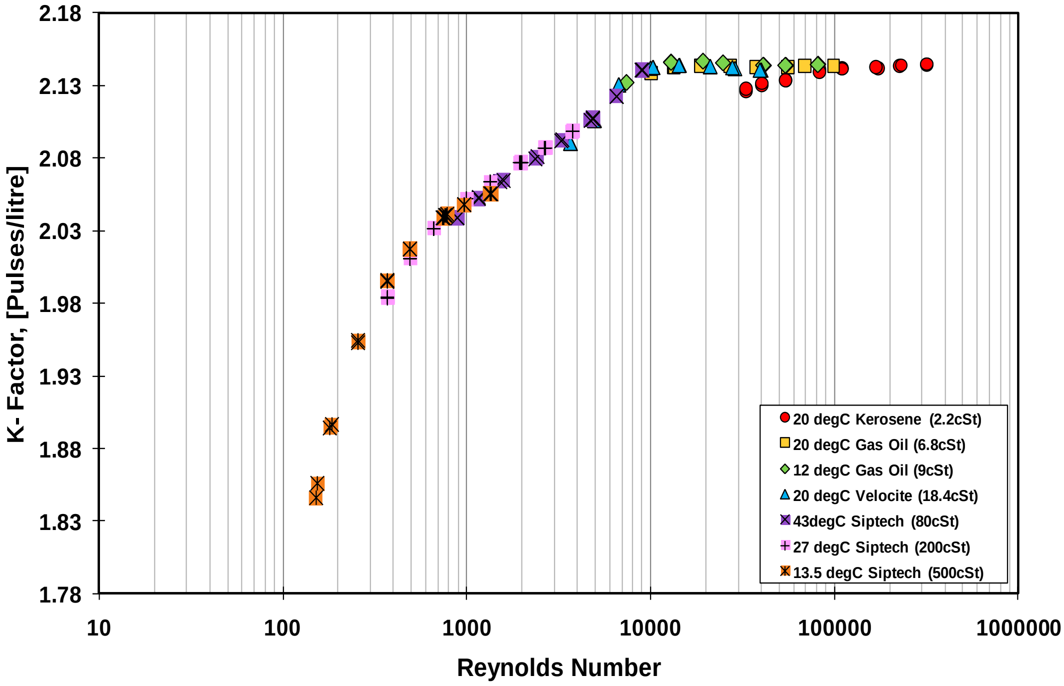


Figure 14 K – factors recorded for the helical blade turbine at various kinematic viscosities and temperatures plotted against pipe Reynolds number.

5.3 Repeatability

The repeatability of the K - factor was assessed simply by comparing the percentage difference between the results for two successive runs at the same nominal flowrate.

Figure 15 shows the absolute value of this difference, plotted against reference volumetric flowrate. Figure 16 shows the absolute value of this difference, plotted against Reynolds number.

Apart from at 30 l/s, there was only one repeat of each test point. As such, the results in Figures 15 and 16 should not be regarded as definitive, and should be utilised from the standpoint of identifying trends.

At 30 l/s, 5 test points were recorded to gain a better estimation of the repeatability of the device. The repeatability for 5 test points was calculated to the 95% confidence level with 4 degrees of freedom. The repeatability was calculated using the following equation:

$$r = \sigma \cdot t \cdot \sqrt{2} \qquad (3)$$

Where:

r	=	Repeatability	σ	=	Standard Deviation
t	=	Students' t			

Repeatability is mostly very good, though there is some indication that it deteriorates slightly at the lower operating end (5 – 15 l/s) of the flowmeter. Neither viscosity nor Reynolds number appears to have any distinguishable effect on the repeatability. All of the test data is within the manufacturer's quoted repeatability of ±0.02 %.

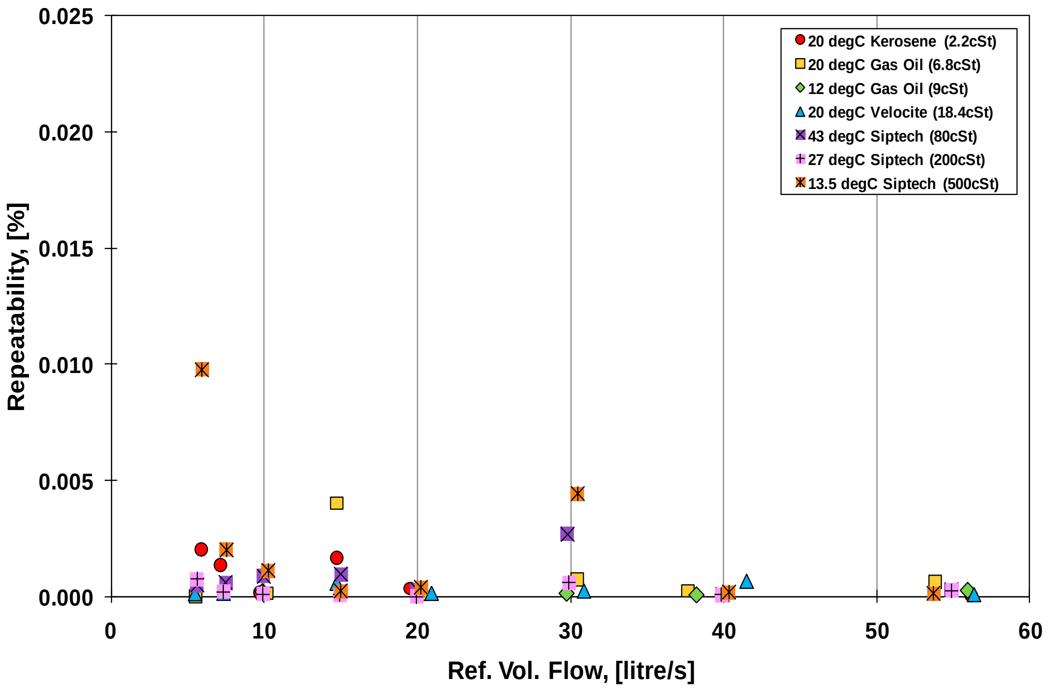


Figure 15 Repeatability recorded for the helical blade turbine at various kinematic viscosities and temperatures plotted against reference volumetric flow.

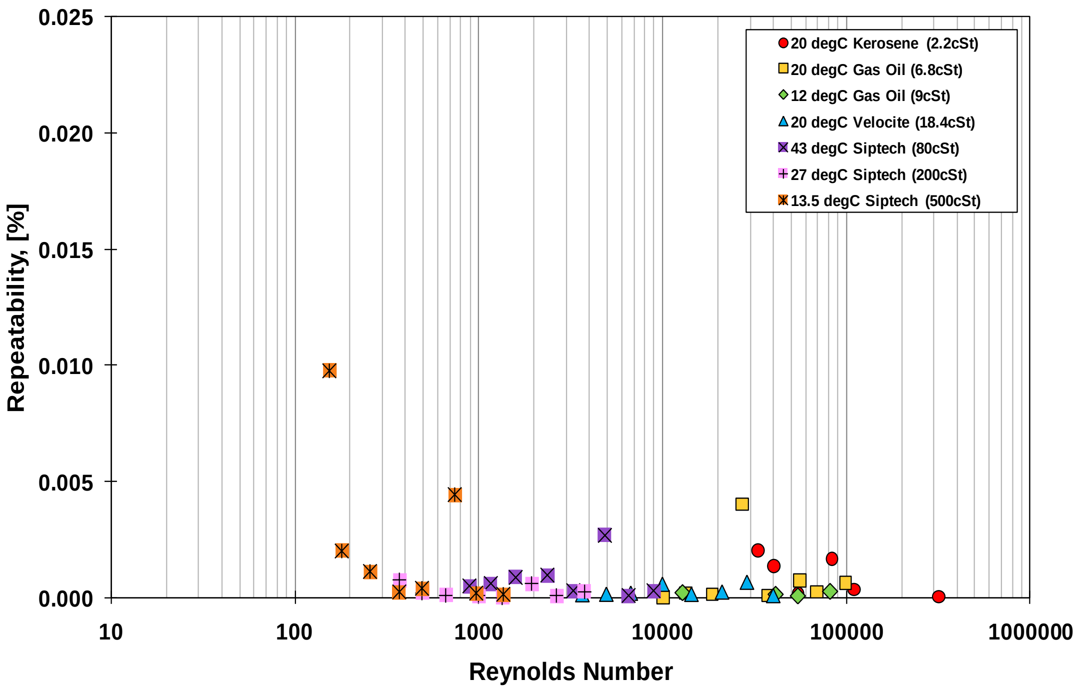


Figure 16 Repeatability recorded for the helical blade turbine at various kinematic viscosities and temperatures plotted against Reynolds number.

5.4 Pressure Drop

Pressure loss is a critical consideration in high viscosity fluid applications, since frictional losses increase with increasing viscosity.

Measurements were made of the pressure drop across the flowmeter for the high viscosity test runs. The measurements were made using a differential pressure transducer separated by 504 mm. The pressure tappings were located 100 mm upstream and downstream from the flanges of the helical blade turbine. As such, the pressure drop was measured across the entire section and not just across the helical blades.

Figure 17 shows the measured pressure drop, denoted by purple (80 cSt), pink (200 cSt) and orange (500 cSt) markers, plotted against the reference fluid velocity. The data appear to show the expected trends.

Also displayed on the graph is the manufacturers predicted pressure drop. These have been plotted for the corresponding test viscosity and are denoted by purple (80 cSt), pink (200 cSt) and orange (500 cSt) dotted lines respectively.

The pressure drop can be calculated using equation four:

$$\Delta P = 3.6 \cdot \rho \cdot \nu^{0.2} \cdot \left(\frac{Q_v}{Q_{v\max}} \right)^2 \qquad (4)$$

Where:

ΔP	=	Dynamic Pressure Drop (PSI)	ρ	=	Oil Density (kg/l)
Q_v	=	Vol. Flowrate (Bbl/h)	$Q_{v\max}$	=	Max Vol. Flowrate (Bbl/h)
ν	=	Oil Kinematic Viscosity (cSt)			

The measured pressure drop at 80 cSt and 200 cSt, purple and pink markers, suggests that the manufacturer's equation for calculating pressure drop appears to overestimate the pressure drop across the device at higher velocities. However, the 500 cSt data, denoted by orange markers, suggests that the equation underestimates the pressure drop incurred by the helical blade turbine at all but the highest velocity.

As mentioned previously, pressure loss is a critical consideration in high viscosity fluid applications and is vital in correctly sizing a flowmeter for its application. The manufacturer's equation for calculating pressure drop does not appear overly robust and potentially needs further investigation.

The maximum pressure drop recorded was 0.506 bar at 6.624 m.s^{-1} for the 500 cSt fluid.

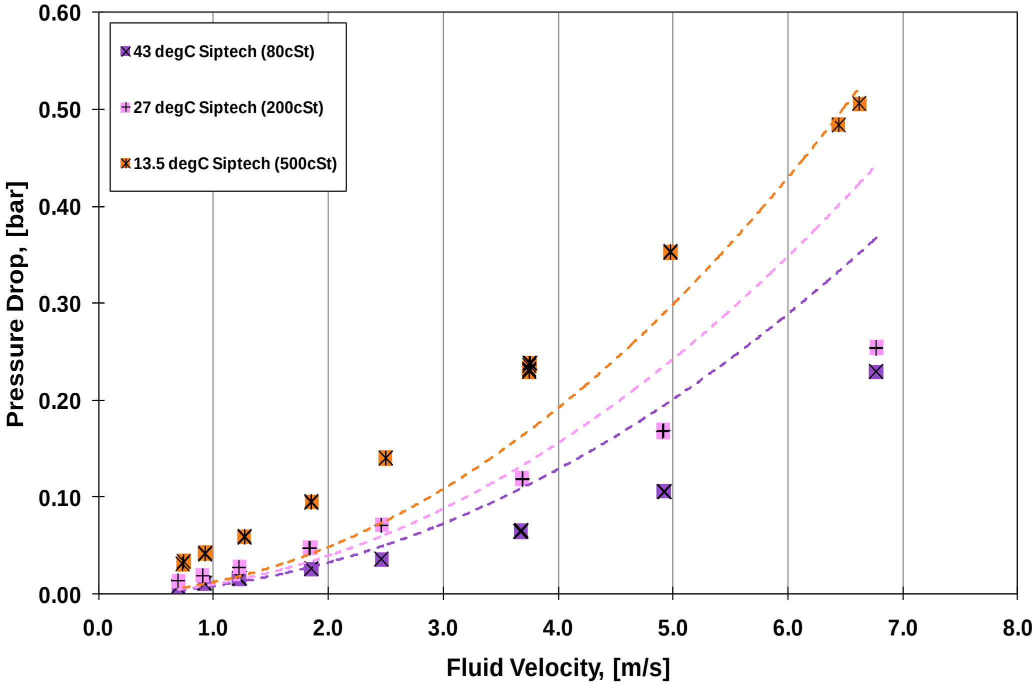


Figure 17 The recorded pressure drop for the helical blade turbine plotted against fluid velocity at three elevated viscosities (80, 200 & 500 cSt). The data points are the recorded pressure drop at the corresponding fluid velocity. The dotted lines are the manufacturers predicted pressure drop at the corresponding fluid velocity.

6 SUMMARY AND CONCLUSIONS

A commercially available 4 – inch helical blade turbine has been operated across a range of kinematic viscosities to investigate some of the technical issues likely to be faced as the demand for accurate heavy oil flow measurement grows. When assessing the suitability of a helical blade turbine for a particularly high viscosity application, the results presented here show that it will be extremely important to calibrate the device in similar conditions as it will encounter in service.

The K – factor of the flowmeter evaluated in this test programme displayed a significant dependence on the liquid viscosity. The measurements recorded exhibited a distinct trend of decreasing K – factor with increasing fluid viscosity at a given flowrate. The results also clearly demonstrated a relationship with the flow profile. As the Reynolds number of the flow decreased, the K – factor of the device decreased.

This paper also explored the effect of operating a helical blade turbine at a different fluid viscosity than the calibration fluid viscosity. The calibration viscosity was 9 cSt and the device was operated at both low (2 – 18 cSt) and high (80, 200 and 500 cSt) viscosities. Using the K – factor recorded at 9 cSt with low viscosity fluids resulted in 95% of the test points having a volumetric flow error of ±0.5 %. For monitoring purposes this appears acceptable. When operating the device with the high viscosity fluids, the volumetric flow errors recorded were much larger and exhibited a clear trend in increasing error with increasing fluid viscosity.

The trend exhibited against Reynolds number suggests that there might be the possibility of calibrating the device in a non standard manner. One possibility would be to calibrate the helical blade turbine meter against Reynolds number and then, using details of the fluid properties, use a 'look-up table system' to predict the K – factor at the corresponding Reynolds number. This might possibly mean that the device would not require calibration at the service fluid viscosity but instead would only require calibration across the service Reynolds number range.

This theory has not been tested and the potential to predict the Reynolds number with a low uncertainty could be problematic. Indeed, regular sampling and monitoring of the service fluid properties would be required. The fluid properties relationship with temperature would also need to be accurately known.

With regards to repeatability, the test results presented here show significant promise for the utilisation of helical blade turbine flowmeters in high viscosity applications. The manufacturer's quoted repeatability is ±0.02 % and in this test programme all of the test data was found to be within ±0.01 %.

The maximum pressure drop recorded was 0.506 bar at a velocity of 6.624 $m.s^{-1}$ for the 500 cSt fluid. The pressure drop model developed by the flowmeter manufacturer was found to overestimate the pressure drop across the device at 80 cSt and 200 cSt at high velocities. It was also found to underestimate the pressure drop incurred with the 500 cSt fluid at all but the highest fluid velocity. As pressure drop is a critical consideration when selecting and sizing a flowmeter for high viscosity applications, it appears that more investigation might be required.

Overall the results reported here reinforce the notion that a conventional liquid flowmeter such as a helical blade turbine cannot simply be relocated from low viscosity to high viscosity service without suitable consideration, characterisation or modification.

7 FUTURE WORK

The experimental programme reported in this paper focussed on testing a 4 –inch helical blade turbine flowmeter with high viscosity fluids up to 500 cSt. The next stage of this project could be to research the effects of different flowmeter sizes and to explore the feasibility of using a Reynolds Number based calibration.

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