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CALIBRATING AND OPERATING CORIOLIS FLOW METERS WITH RESPECT TO PROCESS EFFECTS

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1 INTRODUCTION

The oil & gas industry appear to be favouring a move towards using "newer" and more "advanced" flow measurement technologies such as ultrasonic and Coriolis devices as an alternative to turbine and positive displacement meters. In terms of Coriolis flow meters, they offer the distinct advantage of a direct mass flow and density measurement of the fluid as well as inferred volumetric flow. They also offer diagnostic capabilities and have little installation requirements [1] [2] [3].

Though the adoption of Coriolis flow meters is a logical move, the measurement uncertainty of Coriolis flow meters is not well understood at elevated conditions. Indeed, several factors affecting the performance of Coriolis devices must be highlighted to end users. These include temperature, pressure, fluid viscosity and Reynolds number.

Whilst these effects could potentially be ascertained by calibrating "in-situ" at service conditions, industry appears to be moving away from proving onsite. Partly due to a lack of space, maintenance and cost, provers are becoming scarce in offshore oil & gas applications. The more favoured approach appears to include Coriolis master and duty flow meters [4]. The master meters typically have at least one spare which is periodically sent to an accredited laboratory for a flow calibration.

However, the temperature, pressure and fluid properties of produced oil & gas from a reservoir can differ considerably from standard calibration laboratory conditions. The standard practice for calibrating flow meters for the oil & gas industry has been to match the fluid viscosity and, if possible, the fluid temperature and pressure [5]. Unfortunately, matching all parameters is seldom possible due to the limitations set by the calibration facilities. As such, the parameter that is most often matched is the fluid viscosity. This partly stems from the known effect of viscosity on conventional liquid flow meters such as turbine and positive displacement devices. A limitation of the above approach is that temperature and pressure variations are known to influence properties, other than fluid viscosity, that may also be critical to the overall measurement uncertainty [6].

To address this, NEL built and commissioned a fully accredited elevated pressure and temperature (EPAT) oil flow facility [7]. This facility has been used to investigate the performance of flow meters at elevated pressures and temperatures since 2016. It also enables liquid flow calibrations to be completed close to service conditions.

NEL's traceable Coriolis data can be made available for future updates to the Coriolis ISO standard 10790 [8]. At present, the latest revision in 2015 includes little practical guidance for the operation of Coriolis meters at elevated pressures, temperatures and viscosities.

However, there isn't a complete lack of awareness in industry [4] [6] [9] [10] [11] [12]. Due to the outcomes of NEL research in this critical area, the UK Oil & Gas Authority (OGA) have stipulated that temperature and pressure compensation applied to any flow meter between its calibration conditions and its operating conditions must be "agreed in advance" and must be "traceable and auditable" [13]. Unfortunately, the methodology for calibrating and operating Coriolis meters at elevated conditions appears fragmented.

The purpose of this paper will be to highlight the influence of elevated temperatures, pressures and viscosities and to provide the end user with recommendations for the correct methodology for calibrating Coriolis meters operated at elevated conditions. The paper will also highlight the requirement for the ISO standard 10790 to be updated given the current knowledge level.

2 BACKGROUND

The author has over ten years' experience working in flow measurement at NEL in Glasgow, Scotland. In those ten years, research and commercial work has been completed with a variety of different sized Coriolis flow meters from a range of manufacturers.

In 2008, NEL completed Department for Business, Energy and Industrial Strategy (BEIS) funded research using high viscosity fluids research with Coriolis flow meters up to 300 cSt [14]. An outcome from this work was the upgrade of the UK National Standards oil flow facility to utilise viscous oils up to 2000 cSt. This then evolved into a Joint Industry Project (JIP) for high viscosity fluids and included experimental investigations with several Coriolis flow meters at more viscous conditions [15] [16].

A follow on BEIS funded project in 2011 explored Coriolis, ultrasonic and differential pressure flow meters up to 1500 cSt [9]. All this research, coupled with commercial calibrations using viscous fluids, further enhanced NEL's knowledge and experience of high viscosity and Reynolds number effects on Coriolis flow meters.

In 2011, a major oil & gas operator approached NEL to discuss temperature effects on Coriolis flow meters. The client was replacing the turbine flow meters in their offshore installation with 3-inch Coriolis flow meters and was concerned with temperature effects due to the operating conditions being close to 70 °C.

Whilst Coriolis flow meters have an onboard Resistance Temperature Detector (RTD), it is the tube temperature as opposed to the fluid temperature that is measured. Any disparity between the fluid temperature and tube temperature could result in measurement errors due to the temperature correction algorithms. Furthermore, the robustness of these correction algorithms had not yet been fully verified independently.

To increase the knowledge of this potentially problematic area, in 2012 NEL proposed a Joint Industry Project for Coriolis flow meters at a range of elevated temperatures, pressures and viscosities. This project had over twelve major oil & gas operators as sponsors and was completed successfully in 2014 [11] [17] [18].

Whilst there were several conclusions from the project, the overall conclusion was that there was a substantial requirement for calibrating Coriolis meters close to service conditions. It was found that temperature, pressure and viscosity / Reynolds number effects are significant and can result in the meter deviating by far greater than the 0.1% specification.

Relying on the previous methods of calibrating at ambient conditions in a laboratory and then deploying the Coriolis meters at elevated conditions was deemed to be inappropriate for high accuracy, low uncertainty measurements. A significant barrier was that there was a lack of suitable traceable flow facilities that could calibrate flow meters at elevated temperatures and pressures matching the process conditions.

To remedy this, NEL sought funding from BEIS and NEL's parent company, TUV SUD, to design, build, commission and accredit an elevated pressure and temperature oil flow facility. The facility was fully operational in 2016 and can calibrate flow meters up to 100 l/s, 100 bar.g and 80 °C.

2.1 Coriolis Flow Meter Theory

Coriolis flow meters provide a direct measurement of mass flowrate and product density with stated uncertainties as low as 0.05 % for mass and 0.2 kg/m^3 for density respectively for light hydrocarbons [1] [2] [3]. The exact specification differs by manufacturer and model type. Whilst, the Coriolis forces for gas use are of a magnitude of three times smaller than in liquid use, a Coriolis flow meter can measure single-phase liquid or single-phase gas without any variation in model type [19].

Advantages such as high accuracy, claimed insensitivity to installation and direct measurement of mass flow have led to wide scale adoption across several sectors, including the food, pharmaceutical and process industries [4].

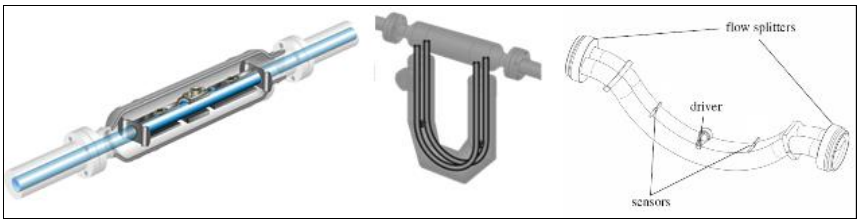

Figure 1 Example of Coriolis Flow Tube Configurations

The Coriolis effect was first documented by the French mathematician and scientist Gaspard-Gustave de Coriolis in 1835 [20]. He established the relationship between forces present when a mass moves in a rotating plane. Coriolis devices utilise this force for flow measurement. The principle measurement method used in Coriolis meters is the use of flow tubes that are vibrated at their natural frequency via a mechanical driver. Electrical pick offs at the inlet and outlet of the device measure any shift via the Coriolis force.

When no flow is present the flow tubes should theoretically display no sign of twist and remain "in phase". Once flow is applied, Coriolis forces produce "twisting" in the tubes resulting in the inlet and outlet being "out of phase" (Figure 2). By measuring these twists, or more correctly the time shift in phase of oscillation of each measuring tube, a mass flowrate can be calculated.

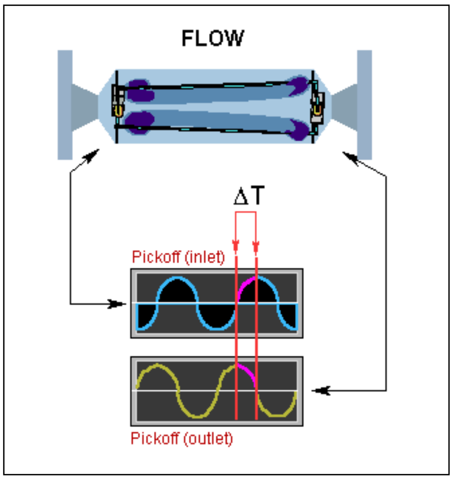

Figure 2 Coriolis flow meter "out of phase"

Due to mechanical tolerances, process effects and even installation, the Coriolis device can be "out of phase" at zero flow conditions and predict a mass flow. This value, although small in absolute terms, can have a large relative effect at low flowrates.

To mitigate this, Coriolis devices can be "zeroed" at zero flow conditions to add or subtract the "zero-stability" when the device is operational. This then theoretically removes any apparent mass flow at zero flow conditions. The robustness of the zero-stability value at alternative pressures, temperatures and viscosities is currently unknown.

Equation (1) details the mass flow calculation deployed by the Coriolis flow meter and the "zero" terms [21].

$$Q_m = FCF\,(\Delta t_m + \Delta t_{live\ zero} - \Delta t_{stored\ zero}) \quad (1)$$

Where

Q_m	=	Mass flowrate
FCF	=	Flow calibration factor
Δt_m	=	Measured time difference caused by the mass flow of the fluid
$\Delta t_{live\ zero}$	=	Measured time due to the live zero value (dynamic)
$\Delta t_{stored\ zero}$	=	Stored zero value (fixed)

It is good practice to check the zero of the Coriolis flow meter upon installation. This confirms whether the device requires a new stored zero value. Coriolis manufacturers recommend that a Coriolis flow meter zero is checked at operating conditions if possible after installation [1] [2] [3].

The zero procedure differs from one manufacturer to another with different specifications and even terms used (Table 1). There is a limit to the value that would constitute an acceptable zero. This also differs by manufacturer, model and meter size.

Table 1 - Coriolis Zero Terms

Manufacturer	**Zero Term**
ABB	% of maximum flow
Emerson MicroMotion	μs
Endress & Hauser	PIPO value
Krohne	% of nominal flow
Rhoenik	Zero counts
Yokogawa	μs

After completing a zero on a Coriolis device, a zero-stability check should be performed via a totalizer check. This ascertains the zero stability and is an extremely helpful method of determining if there are any issues with the Coriolis zero. Unlike the zero terms in Table 1, the units for the totalizer can be standardised to allow for a comparison. A typical unit for this check is kg/hr as this matches the zero-stability quoted by the manufacturer (Figure 3). A generic method used by the author for checking and zeroing a Coriolis flow meter is detailed below.

1. Ensure that installation of the Coriolis flow meter adheres to good measurement practice[1].
2. Flow through the device at moderate velocities for at least thirty minutes to ensure device is close to operating conditions and free of any secondary phase such as gas when liquid is the primary measurement phase.
3. Reduce the flow to zero by closing the valves downstream and, if possible, upstream of the device.
4. Note the assigned mass flow cut-off and stored zero values.
5. Set the device to bi-directional flow.
6. Set the mass flow cut-off value to zero.
7. Perform the zero as detailed by the manufacturer. For some devices this can be a simple push button exercise using the transmitter unit or software on a PC.
8. Good practice states that at least three zeroes should be completed with the zero-value meeting the manufacturer criteria. Ideally, the zero should be better than 50 % of the manufacturer criteria. The last zero obtained will be the stored zero value ($\Delta t_{stored\ zero}$) in use.
9. If the zero is not acceptable then repeat Step 2 for fifteen minutes before reattempting Steps 3 & 7.
10. Once a satisfactory zero has been achieved, the live zero can be checked using the totalizer method.
11. Whilst the flow is still shut off, zero the mass total from the device.
12. Commence totalizer and monitor the mass total over a five-minute period. As the device has been set to bi-directional flow, live monitoring of the flow should indicate both positive and negative flow.
13. After five minutes, check the totalised mass against the sensor specification.
14. If zero is within specification, restore the low flow cut off value.
15. Observe the sensor mass flow reading. It should display zero flow.
16. Set the device to forward or reverse flow as required
17. Restore flow by opening the upstream and downstream valves.

[1] Coriolis flow meters are claimed to be insensitive to installation conditions. However, good measurement practice should be followed. If possible, NEL recommend 5 diameters of straight pipe upstream and downstream of the device.

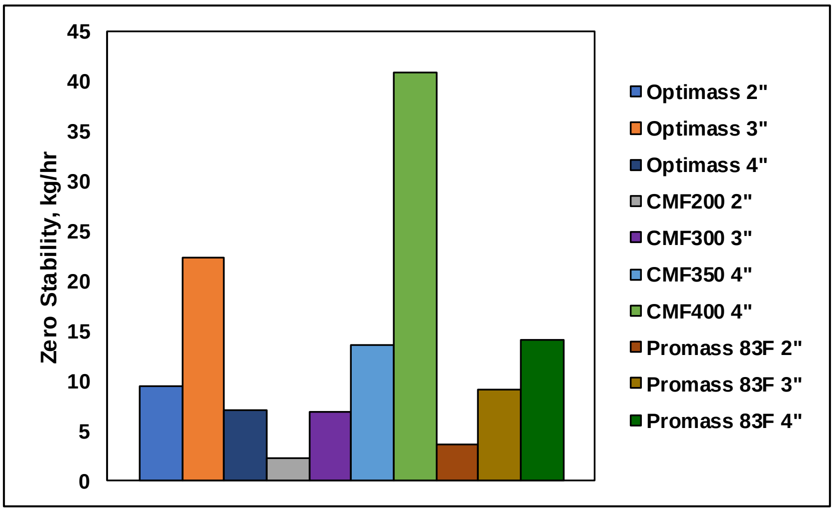

Figure 3 – Zero stability for commercially available Coriolis flow meters

If the zero attained is acceptable, the stored zero value should be equal / greater than the live zero value therefore eliminating any significant zero effect from the meter. The mass flowrate can then be calculated using Equation (2).

$$Q_m = FCF \times \Delta t_m \qquad (2)$$

By zeroing a meter at process conditions, the user is effectively calibrating out any effect of tube rigidity at those process conditions. This means that any variations in meter construction, thermal expansion or contraction of the meter body can be minimised.

2.2 Coriolis Research

Coriolis flow meters were believed to have negligible sensitivity to fluid viscosity [22]. Some manufacturers now accept that Coriolis devices have a sensitivity to flow profile / low Reynolds numbers with viscous fluids [12] [23]. 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.

In terms of pressure and temperature effects, Coriolis meters are not immune to physical changes due to variations in operating conditions. It is known that the Young's modulus of the flow tubes will alter with increasing / decreasing temperature and pressure [6] [10]. This change to the tube stiffness results in an increase / decrease in the ‘twisting’ or’ ‘phase shift’ of the Coriolis device. Bent-shape (also known as “curved” or “u-tube”) Coriolis flow meters appear to exhibit a linear under-read with respect to pressure. Straight-tube devices appear to exhibit a linear over-read with respect to pressure.

To accommodate for these effects, Coriolis manufacturers have corrections incorporated in the flow computer of the device for temperature and pressure variations that are often published in the flow meter manual [1] [2] [3]. The robustness of these corrections still requires further research and analysis. Furthermore, whilst Coriolis meters have a resistance thermometer (RTD) within the device that measures the temperature of the flow tubes, there is no such sensor for pressure.

To correct for pressure effects the user must input the operating pressure into the flow computer or provide a pressure measurement for an online correction. A crucial issue is that the manufacturer stated corrections for pressure are not fully traceable and as such do not meet UK OGA guidelines [13]. The end user must characterise the Coriolis flow meter at the operating temperature and pressure conditions or attain a traceable pressure correction factor via a flow calibration at multiple pressures.

The Coriolis ISO standard 10790 was revised in 2015 but does not include the latest NEL research [8]. The performance of Coriolis meters at elevated pressure, temperature, viscosity and the potential adverse effect of flow profile / low Reynolds numbers are not suitably addressed.

2.3 Scope of Current Work

The scope of work for this project was to explore the performance of Coriolis flow meters that have been calibrated in the Elevated Pressure and Temperature (EPAT) oil flow facility and the UK National Standards oil flow facility at NEL in Glasgow, Scotland. The calibration results have been analysed in terms of fluid viscosity, Reynolds number, temperature, pressure and flow rate to identify trends and to ascertain whether manufacturer claimed performance is valid.

3 NEL

3.1 Elevated Pressure & Temperature Oil Flow Facility

The EPAT flow facility, located at NEL in East Kilbride Scotland, consists of a high (6”) capacity and a low (3”) capacity flow line. These can accommodate nominal pipe sizes from 0.5 to 10 inches and can accommodate up to 10 m of horizontal straight lengths. The facility can operate at line pressures from 4 to 93 bar (g) and temperatures from 20 – 80 °C. The test fluid can be delivered at flowrates up to 360 m^3/hr. Figure 4 displays a SolidWorks schematic of the EPAT facility. Table 2 details the specification of the EPAT Flow Facility.

The facility is operated in recirculation mode and does not flow through the storage tank except at start up and shut down. After filling the loop and purging the system of air, the low-pressure pipework is isolated from the high-pressure recirculation loop. An inline heat exchanger conditions the test fluid temperature to within ±0.2 ºC of a pre-selected value (itself set in the range 20 – 80 ºC). A pressurisation unit maintains the test fluid pressure to within ±0.5 bar of a pre-selected value (itself set in the range 4 – 93 bar). Line temperature and pressure are measured throughout the facility.

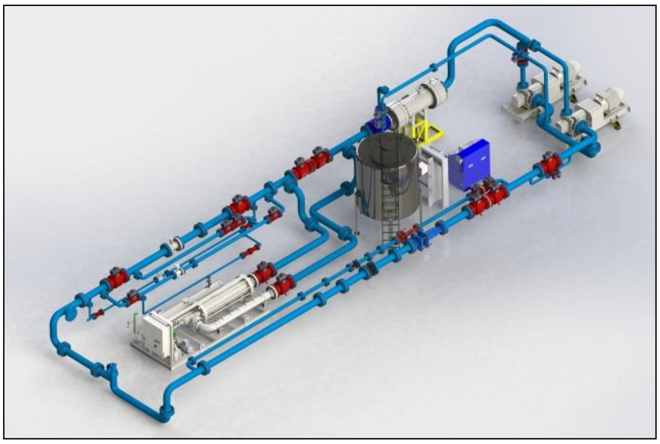

Figure 4 EPAT Facility

Table 2 – Specification of the EPAT Facility

Parameter	Description
Flowrate range	1.5 to 100 l/s
Viscosity range	1.5 to 5 cP
Temperature range	20^{o} C to 80^{o} C
Pressure range	4 bar (g) to 93 bar (g)

The flow facility has a 60 litre (12 inch) compact prover as the dedicated 'primary' reference. The quantity of fluid (volume or mass) which has passed through the device under test can be compared with the quantity which has passed through the compact prover.

For a 'secondary' calibration, the quantity of oil passing through the device under test (DUT) is measured using a reference 'master' meter, installed in series. The reference master meters used at NEL are calibrated at the device under test conditions (temperature, pressure and flowrate). Using this technique, the overall uncertainty in the quantity of mass or volume passed the DUT, expressed at the 95% confidence level, is approximately ±0.08 %.

The EPAT facility uses a mineral oil as the test fluid. Figure 5 below displays a 3D characterisation of mineral oil density when plotted against both pressure and temperature. The viscosity behaviour as a function of temperature is plotted in Figure 6. As density and viscosity are critical parameters and influence the measurement uncertainty of the facility – the properties are measured offline on a periodic basis.

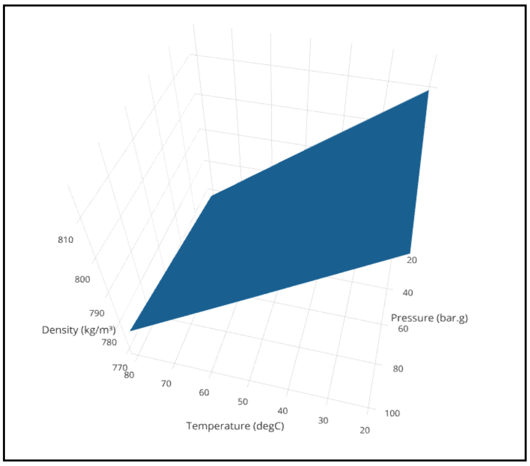

Figure 5 NEL Mineral Oil Density 3D Plot

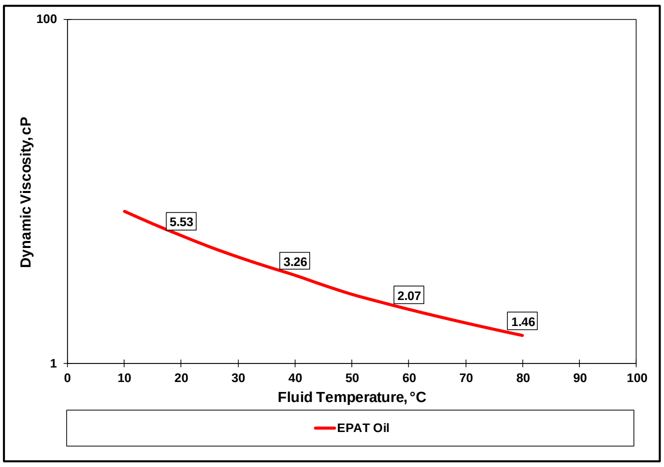

Figure 6 EPAT Mineral Oil Dynamic Viscosity

As the facility is operated at both elevated temperature and pressure and both parameters are known to influence fluid density, the test fluid has been characterised for both parameters. This was achieved using NEL's reference densitometer which itself has been calibrated using reference density fluids across a range of temperatures and pressures. Using this reference densitometer, the fluid density was characterised across the operating range of the facility. This arrangement achieves an expanded uncertainty of 0.025% at the 95% confidence level for measurements in the densitometer and of 0.03% (k=2) in the subsequent estimation of oil density in the test lines.

3.2 Oil Flow Facility

The UK National Standards Oil Flow Facility, located at NEL in Glasgow, 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 10" and can operate at line pressures up to 5 bar. Test fluids can be delivered at flowrates up to 720 m^3/hr. Figure 7 shows a schematic diagram of the flow circuits.

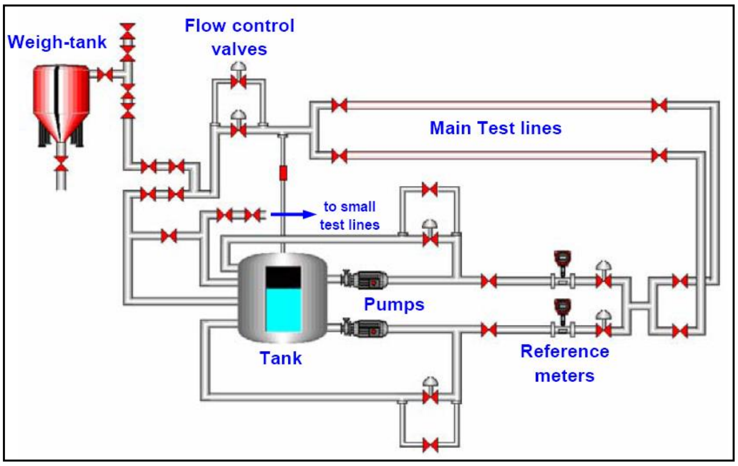

Figure 7 Schematic diagram of the NEL oil flow test facility

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).

Six test fluids are available in this facility – Kerosene, Gas Oil, Velocite, Primol, Siptech and Aztec – covering liquid viscosities from 2 to 2000 cSt. Figure 8 displays the kinematic viscosity of NEL's test fluids for the oil flow facility in 2013.

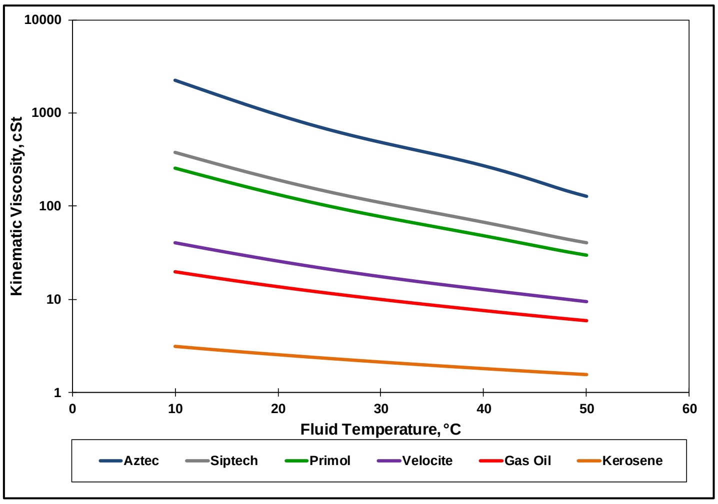

Figure 8 NEL Oil Fluid Viscosities

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.

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 flow meter 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. For oils with a viscosity greater than 30 cSt, typical uncertainties in the quantity of fluid passed are of the order of ± 0.15% at the 95% confidence level.

4 EXPERIMENTAL RESULTS

The experimental results presented here are from a combination of BEIS funded research, Joint Industry Projects, internal NEL research and commercial calibrations. The Coriolis flow meter manufacturers were not active participants in the investigations except for the Joint Industry Projects.

4.1 Temperature Effects

Whilst temperature is a critical parameter for flow measurement, as Coriolis flow meters have an onboard live temperature measurement via the RTD, it has previously been thought that they are not overly affected by temperature. Indeed, Coriolis flow meters incorporate temperature correction algorithms to correct for temperature effects on the flow tube material. The validity of the temperature corrections for all devices from all manufacturers has not been fully ascertained partly due to the large amount of work required. This experimental programme investigated a Coriolis flow meter with and without the temperature correction algorithm enabled.

<u>Meter A – 3-inch Coriolis</u>

Meter A was a 3-inch Coriolis flow meter that was supplied new by the manufacturer. It was calibrated from 20 °C to 60 °C using a kerosene substitute oil. In total, nine calibrations, with three separate zeroes completed at 20 °C, 40 °C and 60 °C, were completed on this device. The data was gathered as part of the Coriolis Joint Industry Project completed in 2014.

The first investigation was completed at 20 °C, 40 °C and 60 °C with a zero attained at 20 °C (Figure 9). The meter over-reads the mass flow for all three calibrations and some points were slightly outside of the manufacturer specification. An adjustment to the mass factor of the device could have been made but it was decided to calibrate the device "as found" in this experimental programme.

From analysing the calibrations displayed in Figure 9 – Figure 11, it appears that zeroing the device at temperature has a small effect on this device. However, it should be noted that zeroing a device will alter the stored zero value in use. Whilst this number is small in absolute terms, it can have a large relative effect at low flowrates.

Unfortunately, the flow range that this device was calibrated across was within the linear turndown of the device. As such, the effect of zeroing the device at temperature can't be easily analysed.

Table 3 displays the zero values for Meter A, when zeroed at 20 °C, 40 °C and 60 °C respectively. The zero value for this Coriolis flow meter manufacturer's devices are presented as a percentage of the nominal flow. The nominal flow for Meter A is 78,000 kg/hr. As such the corresponding stored zero value in kg/hr can be ascertained.

The zero stability for this device is < 3.9 kg/hr. Unfortunately, the zero stability for this meter was not checked as the device was set up by a representative of the manufacturer. In terms of a relationship between stored zero and temperature, there was no immediate trend.

Figure 12 shows that although the temperature effect was significant, it was linear. The mass flow over-reads up to 2 % as the reference liquid temperature increases. This is due to the change in elasticity of the flow tubes loosening with the increase in temperature. This caused the meter Coriolis phase shift to increase and the meter to over-read. However, the linear nature of the effect means that by including an RTD within the Coriolis flow meter, the manufacturer can automatically apply a temperature compensation to the predicted mass flow.

Table 3 – Zero Values for Meter A

Fluid Temperature [°C]	**Stored Zero Value [% of nom. Flow]**	**Stored Zero [kg/hr]**
20	0.030	23.40
40	0.029	22.62
60	0.024	17.94

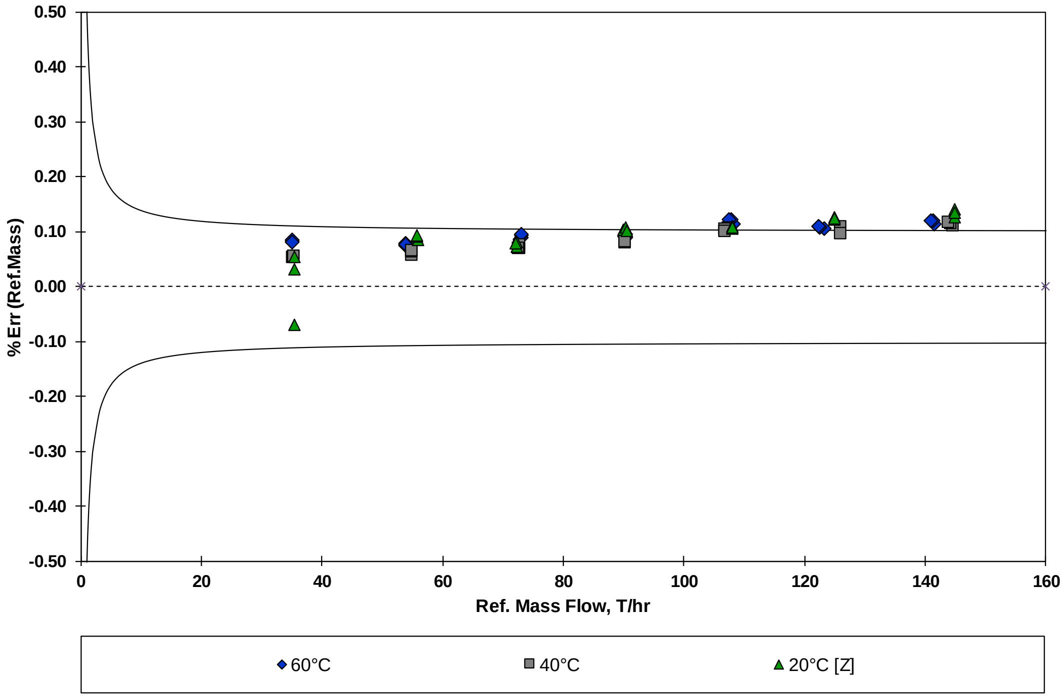

Figure 9 – Meter A mass flow error when zeroed at 20°C

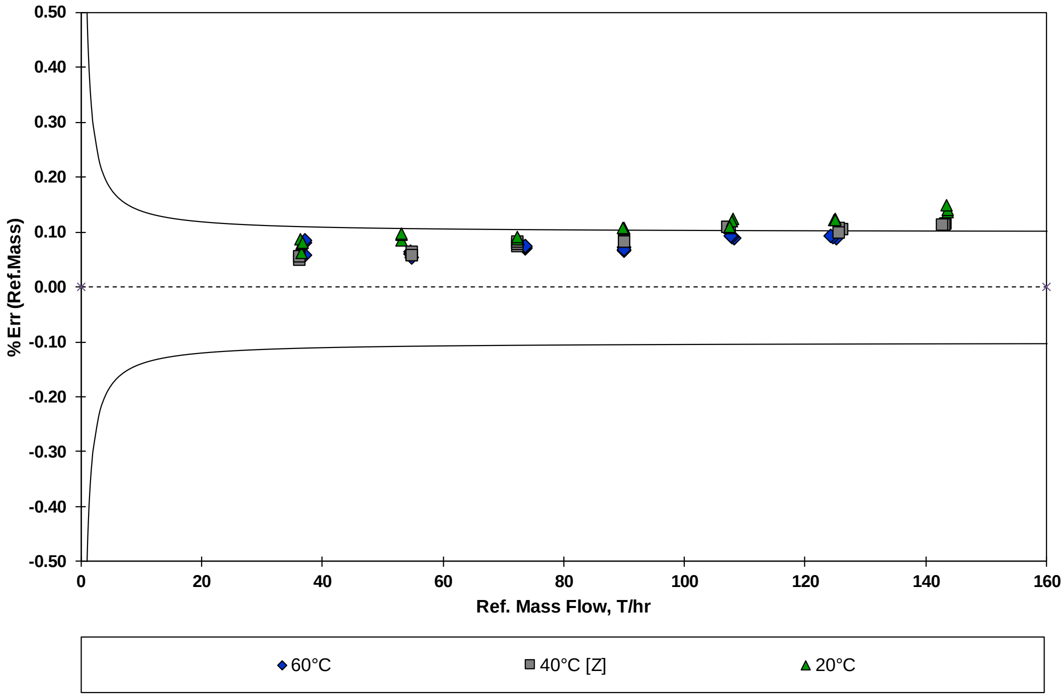

Figure 10 – Meter A mass flow error when zeroed at 40°C

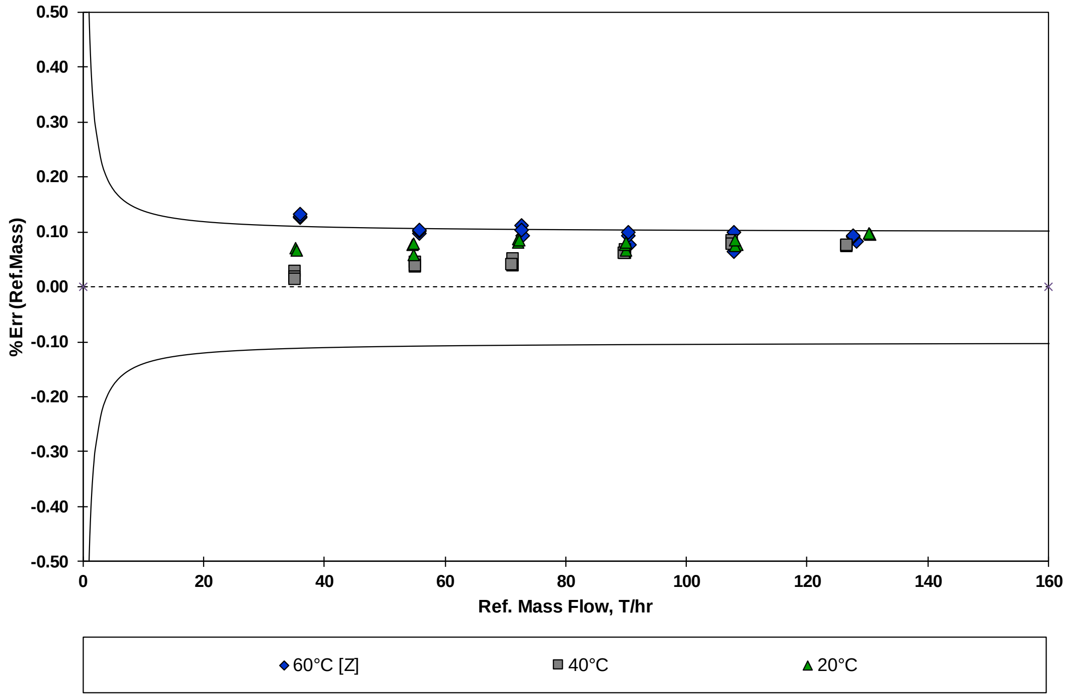

Figure 11 – Meter A mass flow error when zeroed at 60°C

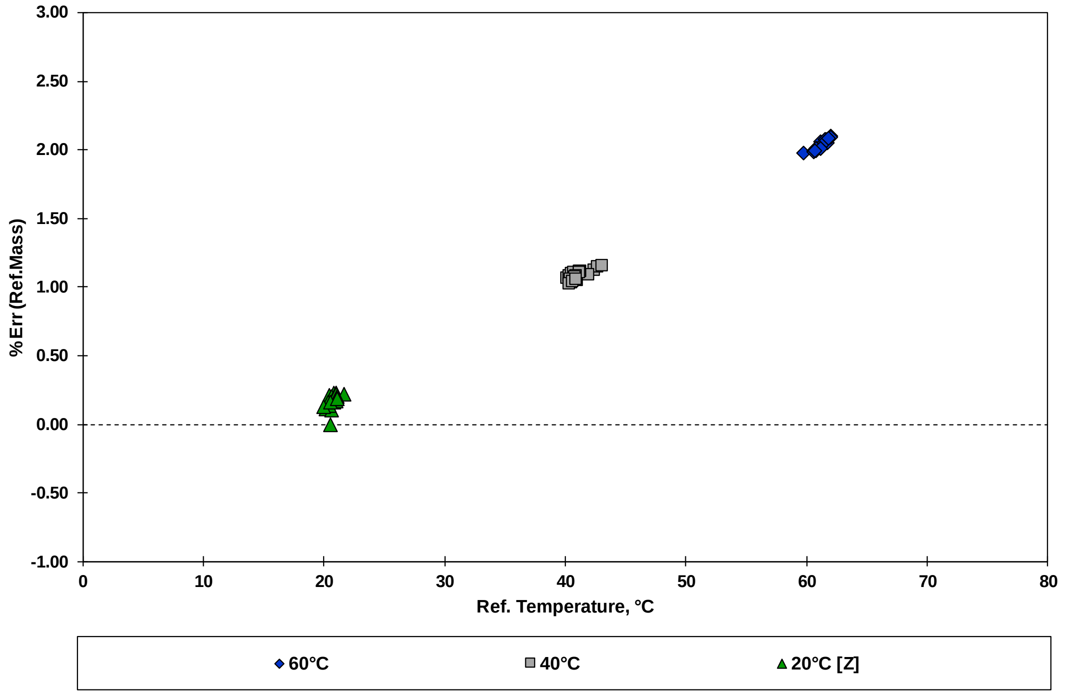

Figure 12 – Meter A uncorrected mass flow error when zeroed at 20°C

4.2 Pressure Effects

Pressure should be a critical consideration for flow meter selection. Whilst pressure compensation values are available for Coriolis flow meters, they have not been utilised in this experimental programme. The results displayed below are for uncorrected mass flow.

<u>Meter B – 6-inch Coriolis</u>

Meter B was a 6-inch Coriolis flow meter that was supplied new by the manufacturer. It was calibrated from 2 bar.g to 40 bar.g in mineral oil at 20 °C. No pressure compensation was activated for this device.

The first calibration was completed with a kerosene substitute oil at 2 bar.g (Figure 13). The meter was outside of the manufacturer specification although could be corrected via an adjustment to the device mass factor. This was not completed as the experimental programme was concerned with pressure effects on uncorrected Coriolis flow meters.

The results for this device display a large dependence on fluid pressure (Figure 14). At 40 bar.g, the Coriolis meter was fifteen times higher the manufacturer specification. Plotting the results against reference pressure in Figure 15 shows that although the pressure effect was significant, it was linear. The Coriolis mass flow output under-read as the reference liquid pressure increased. This was due to the flow tubes stiffening and the Coriolis phase shift becoming smaller as pressure increased. Whilst not ideal, the fact that the pressure effect was linear means that the device could be corrected for the adverse effects via a dynamic compensation factor.

The density output from the device was also measured (Figure 16) and clearly displayed a strong linear dependence with pressure. As with mass flow, this could be caused by the stiffer tubes changing the resonance frequency and as such under-reading the density [6].

If this Coriolis meter was used to measure volume flow without any pressure compensation at an elevated pressure of 40 bar.g then it could be expected for the device to be mis-measuring by greater than 1 %.

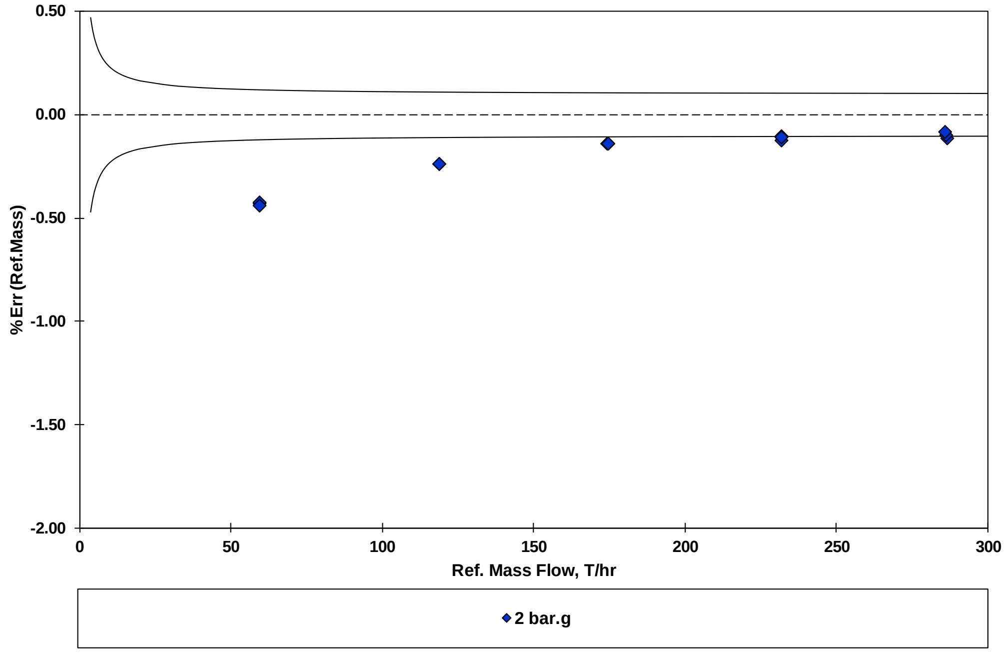

Figure 13 – Meter B mass flow 2 bar.g error

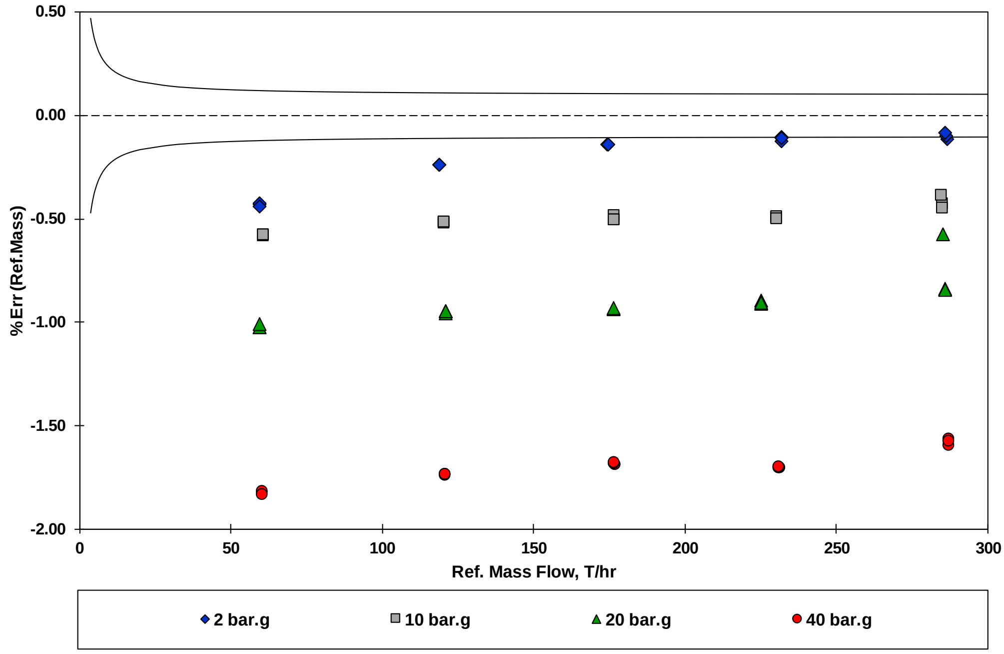

Figure 14 – Meter B mass flow error (2 to 40) bar.g

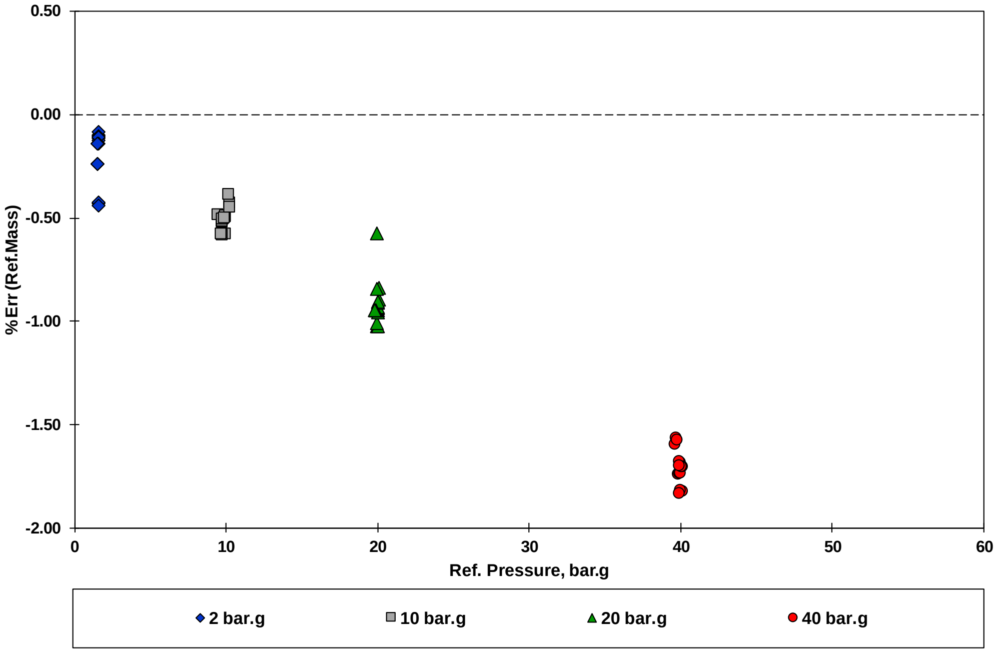

Figure 15 – Meter B mass flow error (2 to 40) bar.g vs pressure

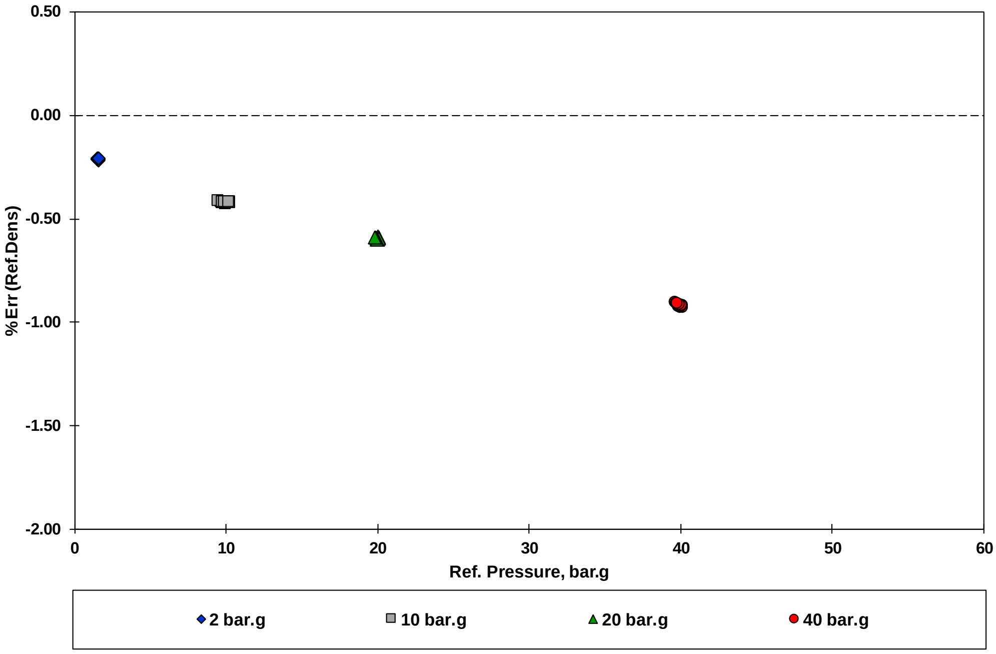

Figure 16 – Meter B density error (2 to 40) bar.g vs pressure

<u>Meter C – 2-inch Coriolis</u>

Meter C was a 2-inch Coriolis flow meter. It was calibrated from 4 bar.g to 60 bar.g in mineral oil at 20 °C. No pressure compensation was activated for this device.

The first calibration was completed at 4 bar.g and was well within the manufacturer specification and displayed excellent linearity (Figure 17). Figure 18 details the performance from 4 bar.g to 60 bar.g with the device exhibiting a clear pressure effect. Excellent linearity was achieved across the range for this device.

The pressure effect for this meter was extremely linear (Figure 19). Although these results are for a different meter manufacturer, model and size than Meter B, the pressure effect was also found to be linear. As mentioned earlier, a linear pressure effect could be corrected via a compensation coefficient.

Whilst the pressure effect for mass flow displayed a negative trend, the density output for Meter C exhibited a positive relationship with pressure (Figure 20). An offset in the density performance of approximately +0.04 % could be corrected via a simple density factor adjustment. As before, performance offsets were not of concern for this experimental programme. Instead the author sought to investigate the relationship between pressure and Coriolis mass and density outputs.

The pressure effect for mass flow for Meter C was approximately one fifth that of Meter B. The pressure effect for density output for Meter C caused an over-read in comparison to the under-read for Meter B. The relative effect was approximately one seventh that of Meter B. This illustrates that different meter design, resonant frequency, sizes, model type and manufacturer can have an influence on the effects of pressure.

The published pressure compensation coefficient for this device was stated as -0.008 % per bar.g. The calculated pressure compensation coefficient from the traceable data in this investigation was found to be -0.00827 % per bar.g. It can be stated that for this device, the published pressure compensation coefficient was found to be rather accurate.

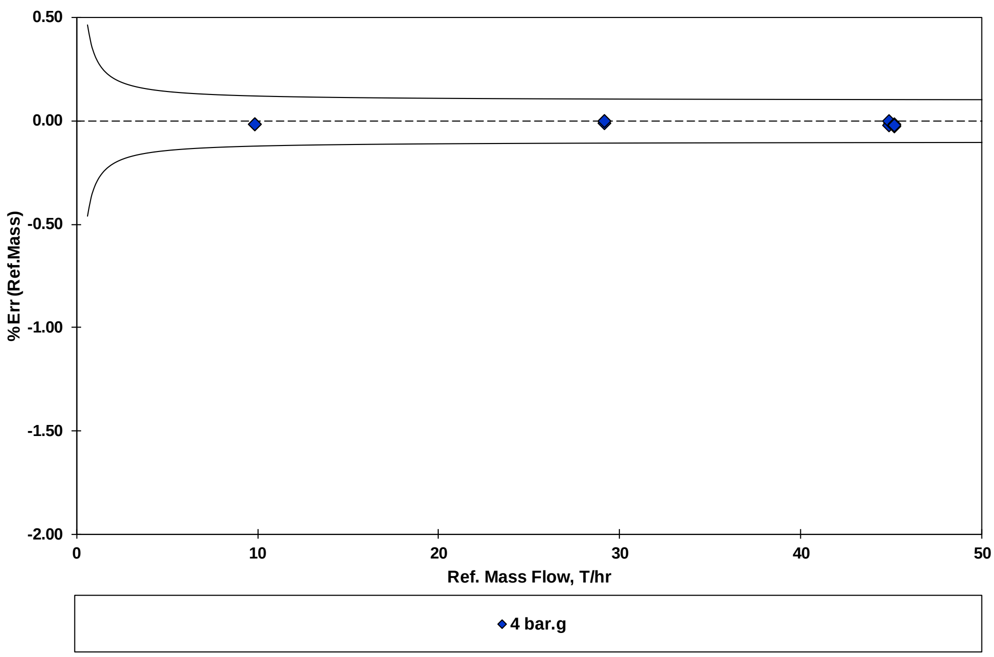

Figure 17 – Meter C mass flow 4 bar.g error

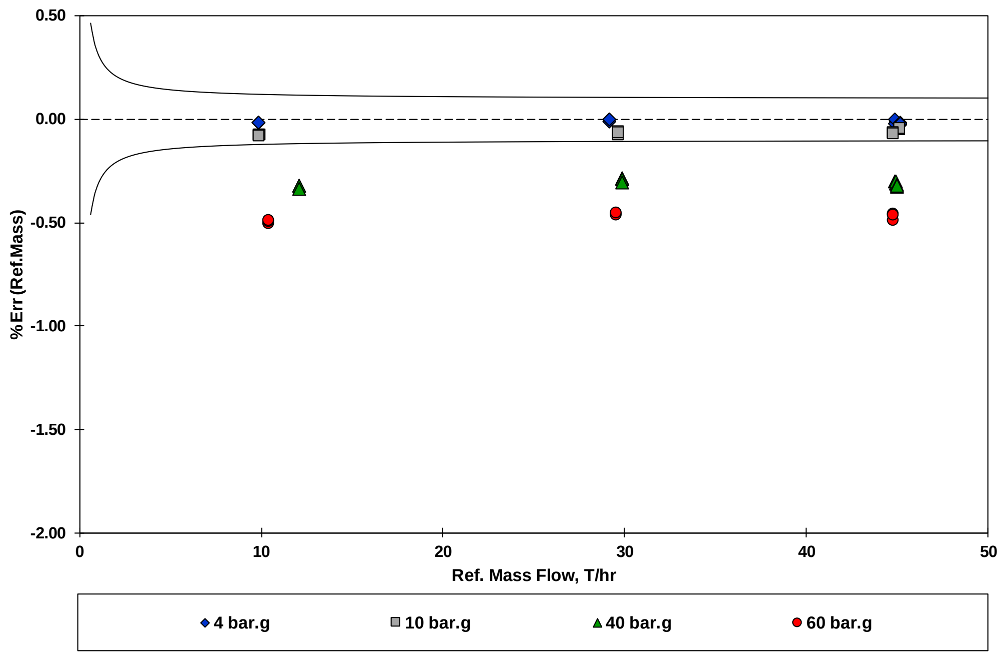

Figure 18 – Meter C mass flow error (4 to 60) bar.g

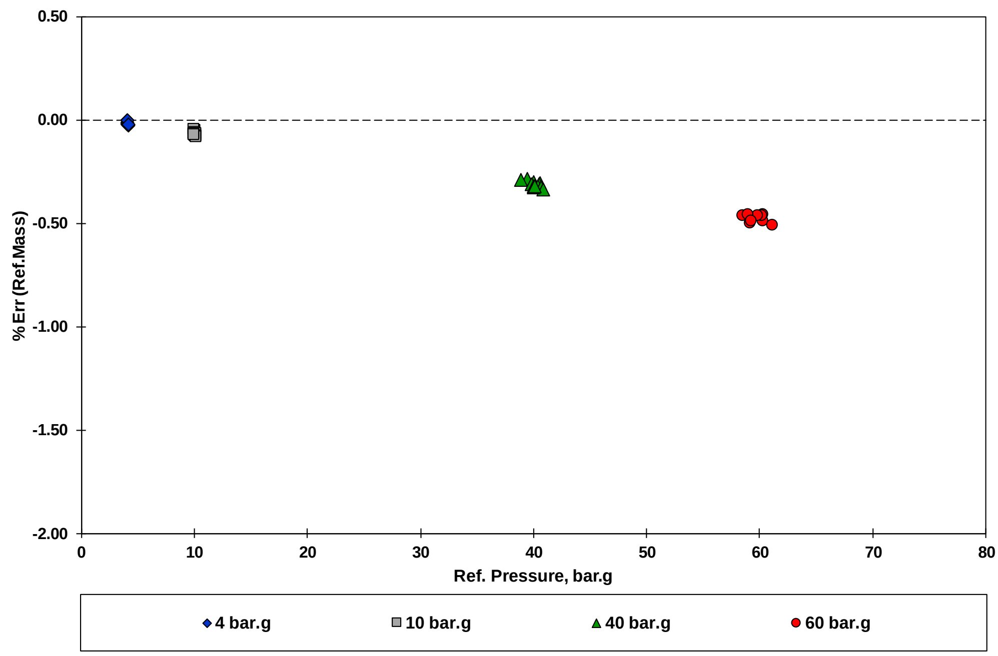

Figure 19 – Meter C mass flow error (4 to 60) bar.g vs pressure

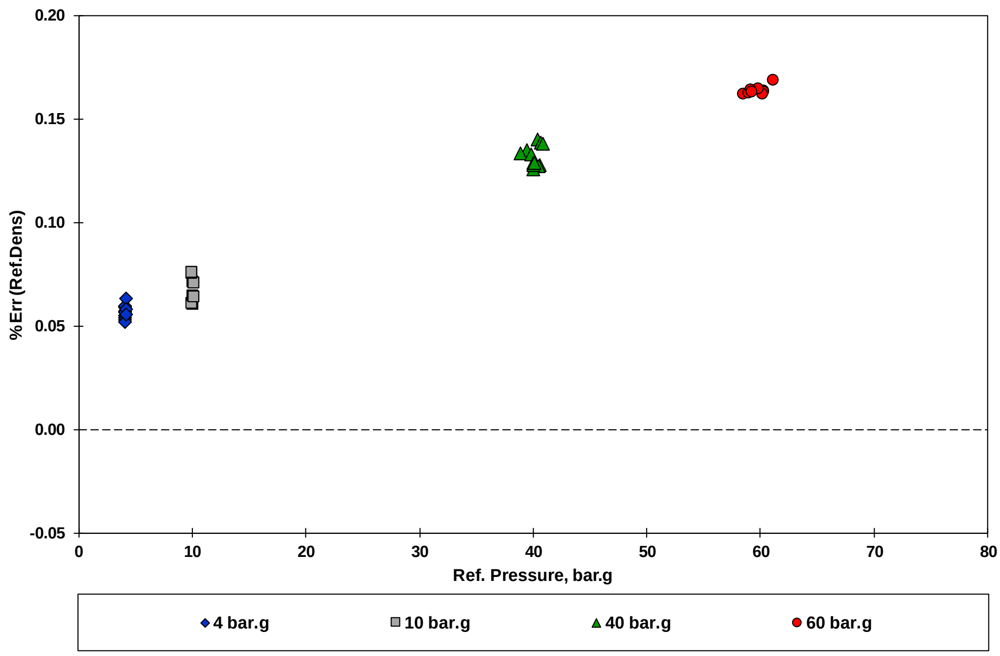

Figure 20 – Meter C density error (4 to 60) bar.g vs pressure

4.3 Viscosity / Reynolds Number Effects

Viscosity is a critical parameter in flow measurement. Traditional flow meters such as turbine and positive displacement meters are known to be highly affected by fluid viscosity. Historically, Coriolis meter manufacturers have been thought as being insensitive to viscosity effects.

In terms of Reynolds number effects, as Coriolis flow meters are unaffected by installation conditions, it was also assumed that any adverse effects from the velocity profile variations in laminar, turbulent and transitional flow would be negligible.

<u>Meter D – 4-inch Coriolis</u>

Meter D was a 4-inch Coriolis flow meter. It was calibrated using two test fluids at NEL at 10 °C, 20 °C, 30°C and 40 °C. One was a light fluid similar in viscosity to Kerosene (2 cSt to 3 cSt). The other was a relatively viscous oil (50 cSt to 300cSt) with the trade name “Primol”.

The results for the light fluid, “Kerosene” at all four viscosities / temperatures are well within the manufacturer specification (Figure 21) with no temperature effect apparent.

Figure 22 demonstrates a clear effect of viscosity on the meter performance. At higher viscosities the experimental data was outside the manufacturer specification. Separate curve fits for the data could potentially be applied for each viscosity. The data stresses the importance of calibrating a Coriolis meter at the service conditions. Small changes in temperature can produce large variations in fluid viscosity which can have significant effects on the performance of Coriolis flow meters.

A clear linear trend with pipe Reynolds number can be witnessed from Figure 23. The outliers are zero stability effects from the 10 °C (3 cSt), 30 °C (80 cSt) and 40 °C (50 cSt) calibrations. Correcting a Coriolis meter for Reynolds number certainly shows promise from these results.

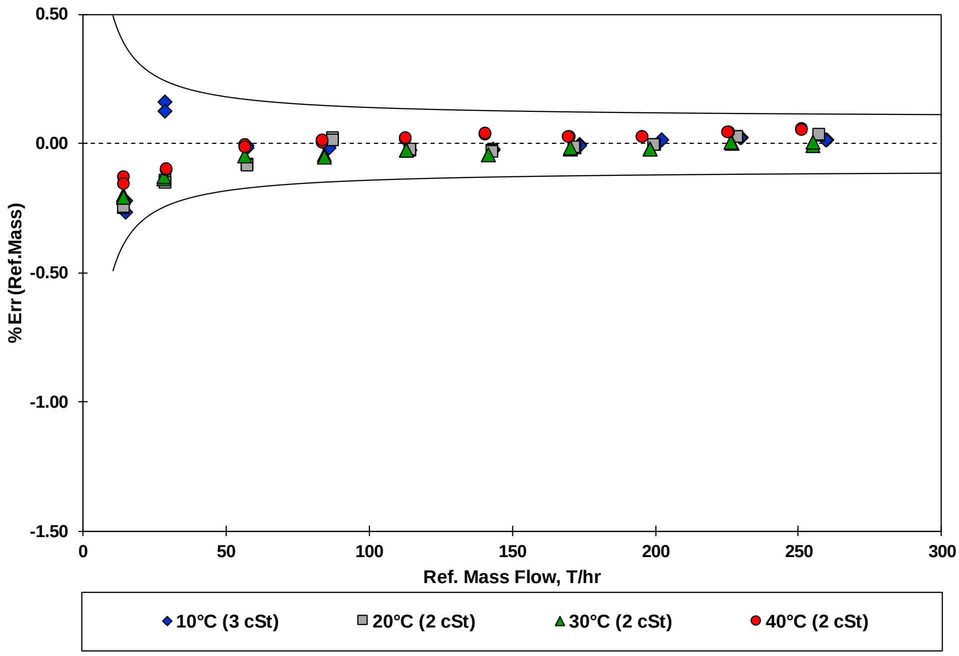

Figure 21 – Meter D mass flow (2 to 3) cSt error

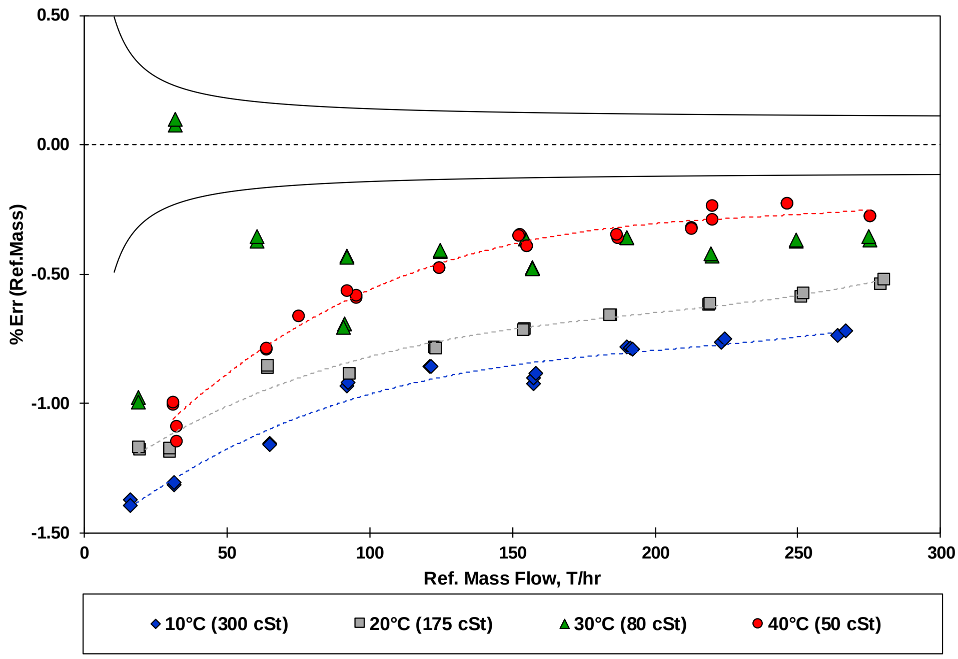

Figure 22 – Meter D mass flow (50 to 300) cSt error

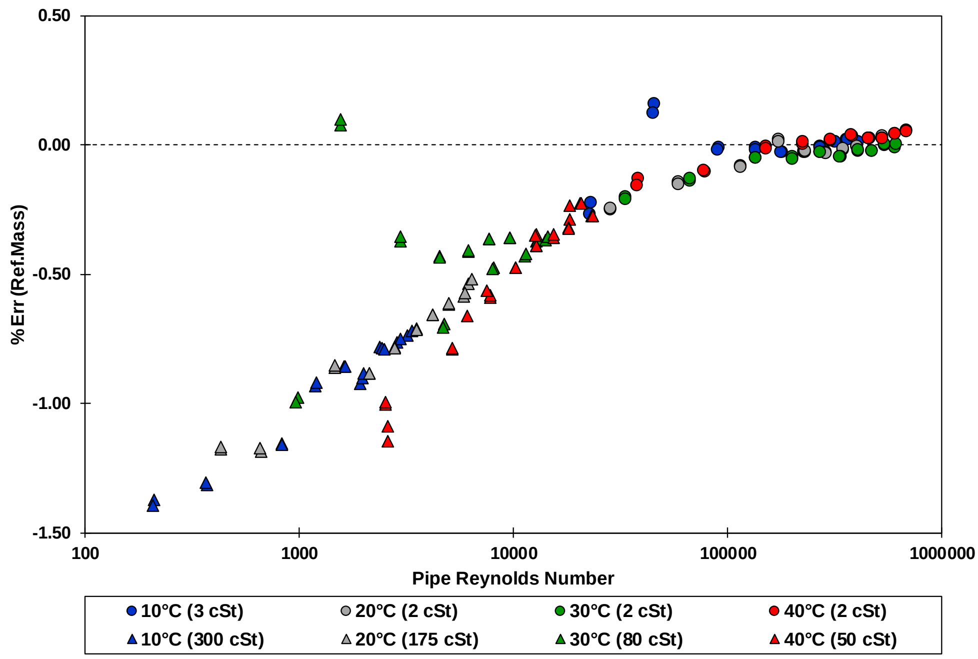

Figure 23 – Meter D mass flow (2 to 300) cSt error vs pipe Reynolds number

<u>Meter E – 6-inch Coriolis</u>

Meter E was a 6-inch Coriolis flow meter. It was calibrated using one viscous test fluid at NEL at 200 cSt, 600 cSt, 1000 cSt and 1500 cSt by altering the fluid temperature.

The device has a patented Reynolds number correction. The device calculates the Reynolds number of the flow from equation (3).

$$Re_C = \frac{4 \cdot Q_m}{\pi \cdot D_T \cdot \mu} \quad (3)$$

Where

Re_C	=	Coriolis meter Reynolds number
Q_m	=	Coriolis mass flow
μ	=	fluid dynamic viscosity
D_T	=	Coriolis tube diameter

The device determines the fluid dynamic viscosity via the tube dampening signals and applies correction factors that are theoretically derived and empirically validated. The correction is normally applied for transitional and laminar flow regimes. The exact number at which the correction is activated has not been disclosed.

With this Reynolds number correction in mind, the device was calibrated in two separate phases during NEL's experimental investigation. The first phase was completed at 600 cSt and 1000 cSt with the Reynolds number correction disabled (Figure 24). Figure 25 displays the same set of uncorrected results but displayed with respect to pipe Reynolds number. Like Meter D, the device exhibited a clear Reynolds number effect.

The second phase with Meter E was completed at 200 cSt, 600 cSt, 1000 cSt and 1500 cSt with the Reynolds number correction enabled. Crucially this phase was completed at the highest and lowest viscosities without the manufacturer completing any prior calibrations at these viscosities (200 cSt and 1500 cSt). The data shown in Figure 26 shows that whilst the device was not within the manufacturer specification of 0.1 %, the majority of the data was within 0.25 %.

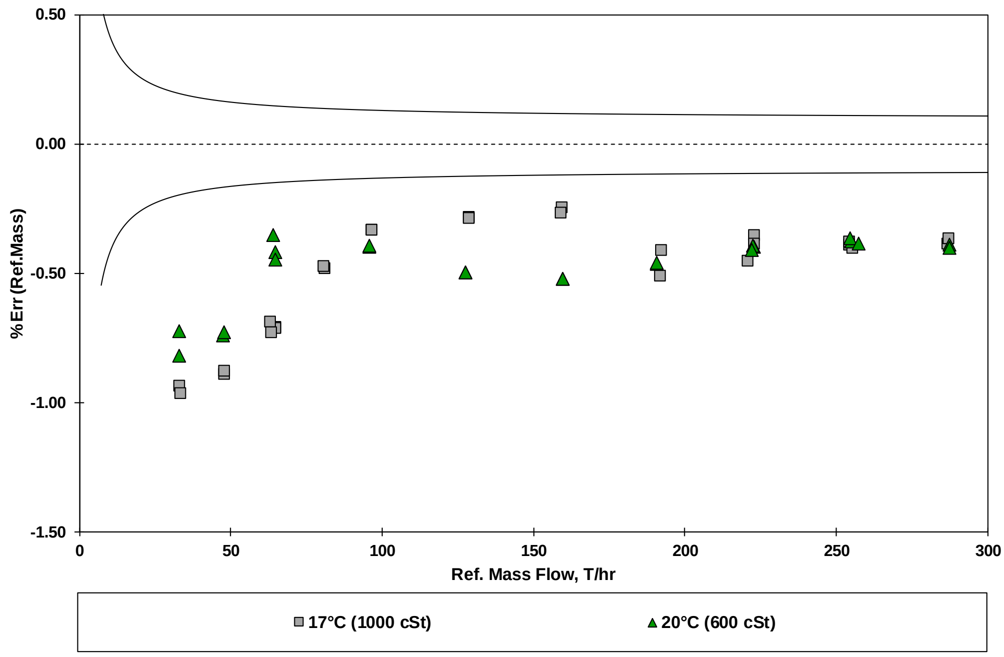

Figure 24 – Meter E uncorrected mass flow error

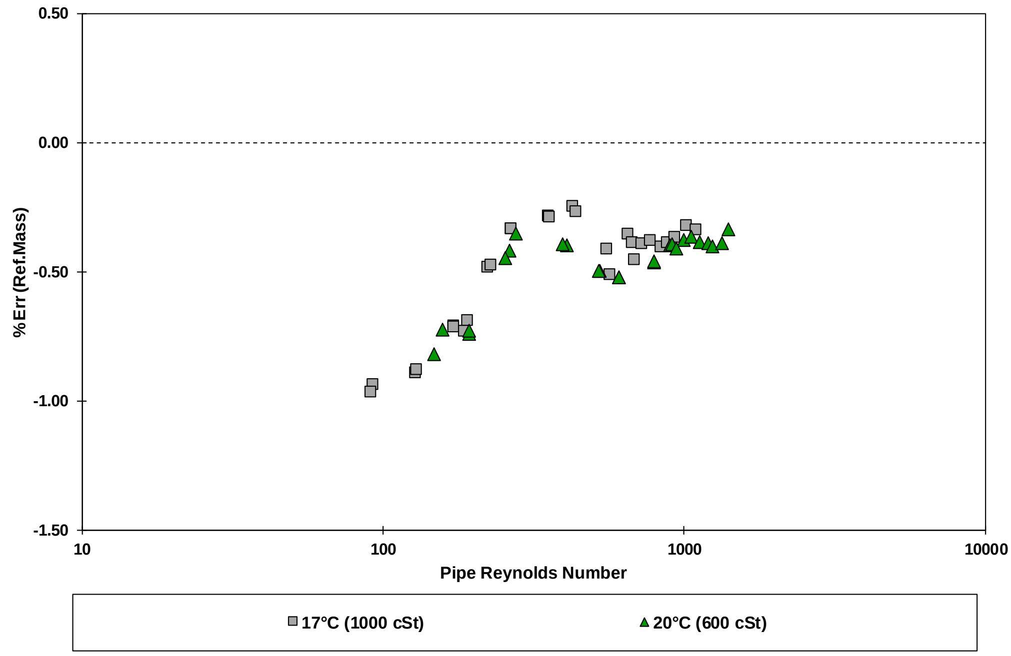

Figure 25 – Meter E uncorrected mass flow error vs pipe Reynolds number

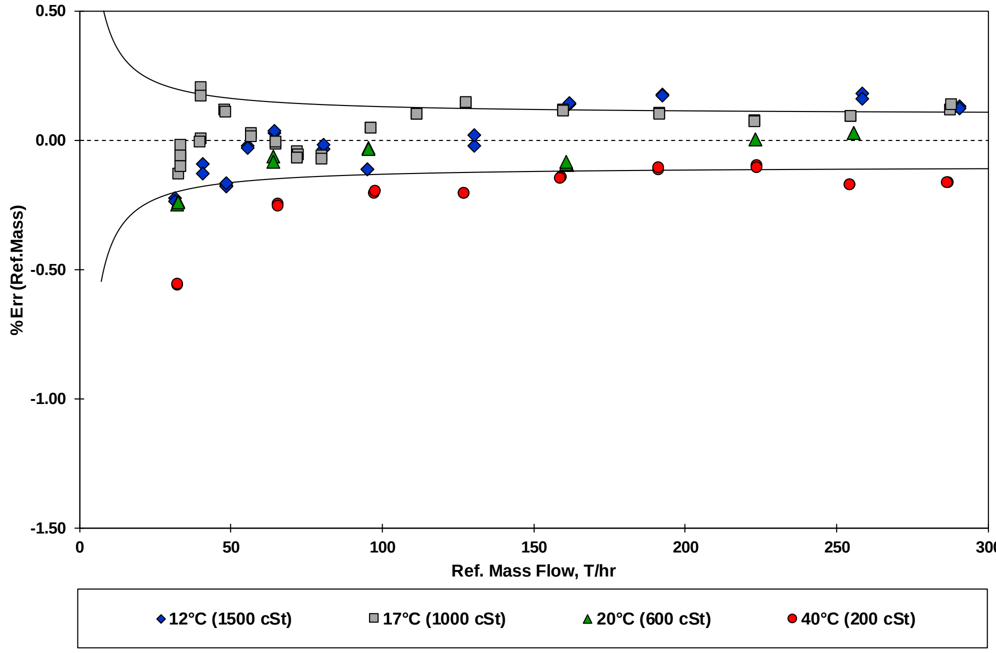

Figure 26 – Meter E corrected mass flow error

5 DISCUSSION

A range of commercially available Coriolis flow meters have been operated across a range of pressures, temperatures and viscosities to investigate some of the technical issues likely to be faced in service. When assessing the suitability of a flow meter for a particularly 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 **temperature** of the fluid can cause changes Coriolis sensor's material elastic properties. As the temperature increases, the flow tubes become less stiff and can potentially over-read the mass flow [24]. To compensate for this effect, all commercial Coriolis are equipped with a RTD that automatically corrects for the effects of temperature. However, this temperature measurement for Coriolis flow meters is located on the outside of the flow tubes. This could result in a significant temperature lag between the fluid temperature and flow tubes depending on temperature variations and even external conditions.

It also means that the temperature correction employed by the Coriolis flow meter is only as good as the temperature probe. If the RTD has a high uncertainty, then so too will any correction algorithm. Furthermore, RTDs are known to drift between calibrations. To the authors knowledge, no Coriolis flow meter RTD is calibrated on any specific calibration interval.

The **pressure** of a fluid can affect the elasticity (Young's modulus) of the measurement tubes of a Coriolis flow meter [10]. As the pressure increases, the rigidity of the flow tubes increases causing a decrease in Coriolis forces and an under-read of the mass flow. For certain Coriolis designs, as the pressure increases the curved tubes stiffen and attempt to straighten to their original tube form (Bourdon Effect).

The pressure effect has been shown to be linear and can be corrected either via an adjustment to the meter mass factor, a static fixed pressure correction or a dynamic "live" correction via a pressure transmitter. However, the reproducibility of this coefficient has not be ascertained. Flow meters are known to drift. Does the pressure effect shift between calibrations? Does cycling the pressure of the fluid have a detrimental effect on the magnitude of the pressure compensation required? These questions will only be answered by further research into this area and analysis of repeat calibrations using NEL's EPAT facility.

Historically, Coriolis flow meters were not believed to be susceptible to **viscosity / Reynolds number** effects. Figure 23 clearly illustrated that there is indeed a notable Reynolds number effect for **certain** Coriolis flow meters. There has subsequently been research by universities and also Coriolis flow meter manufacturers into this important area [12] [23]. An important term for Coriolis flow meters and Reynolds number effects is the "Aspect Ratio", α. It can be defined using Equation (4).

$$\propto = \frac{L}{r} \quad (4)$$

Where

α	=	Aspect ratio
L	=	Coriolis tube length
r	=	Coriolis tube radius

Kutin et al [23] performed an investigation into Coriolis devices with an Aspect Ratio of 30 and 60. They found that devices with lower Aspect Ratios display a larger velocity profile effect. The Aspect Ratios for some commercially available Coriolis flow meters can be found in Figure 27. The values calculated by the author are merely approximations from the tube length and diameter stated in the device manuals. Only Emerson MicroMotion and Endress & Hauser were found to publish their Coriolis dimensions. Indeed, many manufacturers do not report the tube length and diameter.

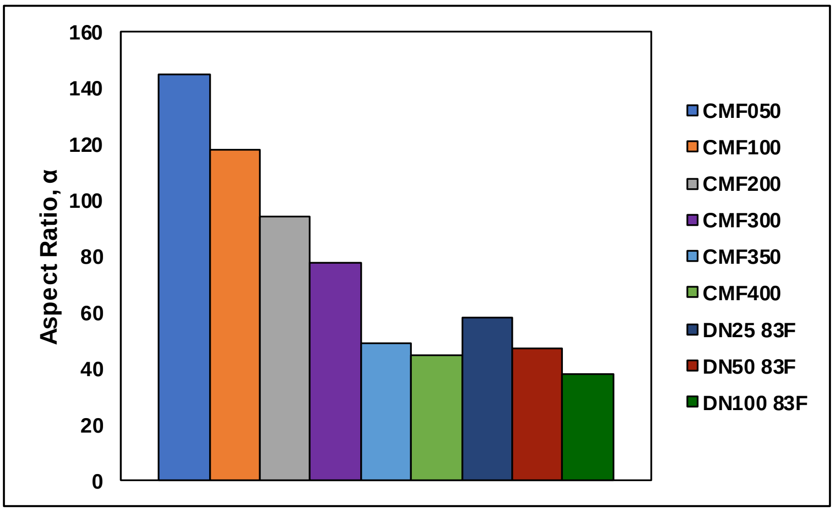

Figure 27 – Aspect Ratio for commercially available Coriolis flow meters

Tschabold et al [12] also explored viscosity / Reynolds number effects on Coriolis devices. In their paper they state that the Reynolds number effect is a consequence of viscous shear forces dampening the Coriolis force and producing a smaller phase shift. The thicker the boundary layer due to Reynolds number, the more significant the effect. Consequently, the thicker boundary layer equates to a smaller phase shift which results in the Coriolis device under-reading the mass flow in a linear manner with Reynolds number.

A question that might be asked is how well does a calibration transfer when 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. The experimental data illustrates that calibrating the device at 50 cSt and then using it at 300 cSt could cause deviations greater than 0.5 % (Figure 22). That would mean that the Coriolis device would have deviations approximately five times larger than the specification of the device.

Regarding any Reynolds number-based corrections, the patented compensation appears to show some promise. However, a major caveat regarding the validity of the correction would be the Reynolds number at which the flow is deemed as transitioning between the laminar and turbulent flow regimes. It has been shown that laminar-transitional flow is dependent on entry lengths [25] [26]. Indeed, laminar flow has been found to occur up to 100,000 Reynolds number in rare circumstances [27]. It would be interesting to complete a future investigation of these devices with different entry lengths prior to the device.

6 RECOMMENDATIONS

To aid the end user, the author has the following recommendations for calibrating Coriolis flow meters when onsite proving is not available. From experience, pressure effects are more significant than temperature effects. Viscosity / Reynolds number effects can be significant and should be considered.

Temperature

The temperature compensation coefficient cannot be easily modified by the end user[2]. Instead, a more practical approach would be to calibrate the device as close to the service temperature as possible. This would allow the end user to ascertain whether temperature effects are significant and should be corrected for via an adjustment to the Coriolis mass factor.

A calibration procedure recommended by the author for temperature effects is detailed below.

1. Zero device at operating temperature & pressure
2. Calibrate device at operating temperature & pressure ‘as found’
3. Perform calibration at ±10 °C to determine temperature offset
4. If required perform an ‘as left’ calibration

[2] Some manufacturers allow the temperature correction factor to be modified via software. However, this is not standard practice.

Pressure

A traceable pressure correction should be used where possible. If the process conditions are stable[3], then a static fixed pressure correction could potentially be applied. A static fixed correction refers to the device being adjusted for the effects of pressure via an adjustment to the device mass factor or to the flow computer. However, it should be noted that if the pressure effect is significant (e.g –0.020 % per bar.g) then even a 5 bar.g variance could produce a meter offset of –0.10 % using a static fixed correction.

The preferred method would be to use a dynamic "live" correction via a pressure transmitter. This utilises a pressure measurement at the Coriolis flow meter that is either supplied to the Coriolis transmitter or to a flow computer to adjust the meter for the effects of pressure. The meter compensation coefficient would still be a set value, but the amount of adjustment to the Coriolis flow meter will vary with the measured pressure.

A calibration procedure recommended by the author for pressure effects is detailed below.

1. Zero device at operating temperature & pressure
2. Calibrate device at operating temperature & pressure 'as found'
3. Additional pressure compensation calibration at ± 10 bar.g to derive (linear) pressure compensation coefficient
4. If required, adjusting the Coriolis mass factor and then perform an 'as left' calibration
5. NEL pressure correction is fully traceable and meets OGA Regulations

Viscosity / Reynolds Number

Correcting for the adverse effects of viscosity / Reynolds number can be challenging. Depending on the manufacturer, the device might apply a Reynolds number correction. It should also be noted that installation has a significant effect on the Reynolds number at which the laminar-turbulent transition occurs. Hence, the robustness of any Reynolds number correction might require further investigation at alternative entry lengths.

A calibration procedure recommended by the author for viscosity / Reynolds number effects is detailed below.

1. Specify Reynolds number range of device from service condition density, viscosity and flowrate
2. Match Reynolds number range with high viscosity fluid at two or more temperatures at an accredited flow laboratory
3. Where possible, recreate the installation entry lengths
4. Zero device at close to operating conditions if feasible
5. Calibrate device at Reynolds number 'as found'
6. Decide if Reynolds number effect is significant
7. If required, perform an 'as left' calibration

[3] For the purposes of this paper, stable process conditions are deemed as the pressure not varying by more than ± 5 bar.g.

7 CONCLUSIONS

Overall the results reported here reinforce the concept that Coriolis flow meters cannot simply be utilised at service conditions without suitable consideration, characterisation and calibration. In summary.

- A Coriolis water calibration does not replicate service conditions
- Manufacturer published pressure corrections are not fully traceable at present
- Temperature effect is magnitude less than pressure effects due to a combination of manufacturer R&D and the inclusion of a RTD measuring the Coriolis tube temperature
- A traceable dynamic "live" pressure correction via a pressure transmitter should be used where possible
- If operating in high viscosity conditions, a Coriolis flow meter should be characterised against Reynolds number with a suitable fluid to ascertain the effects
- The performance of Coriolis meters from one manufacturer to another are not necessarily similar as there are many other variables such as Aspect Ratio, model design, patented corrections and the quantity and quality of internal R&D completed

8 FUTURE WORK

It is the authors opinion that ISO 10790 (Measurement of fluid flow in closed conduits -- Guidance to the selection, installation and use of Coriolis flow meters) [8] should be updated in the near future with the latest available traceable data on temperature, pressure and viscosity / Reynolds number effects.

A future journal / conference paper by the author will present an extensive set of pressure data for multiple Coriolis flow meters that have been calibrated at NEL's EPAT flow facility. Pressure compensation coefficients, drift, linearity and repeatability will all be analysed and reported. This data will be made available for any subsequent update of ISO 10790.

Additional research completed by the author will be reported via a future journal / conference paper and will explore the transferability of a Coriolis water calibration to a gas calibration. This calibration method is currently being used by some in industry but there appears to be a lack of traceable data to validate the practice. The effects of zero stability will also be reported in this investigation. This will include the effects of applying an incorrect zero to a Coriolis device. This partly replicates the occasionally observed and unfathomable practice of deliberately not zeroing a Coriolis flow meter in service or prior to a calibration.

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