Good Practice Guide:

Coriolis Flow Meter

National Engineering Laboratory

Department for Business, Energy & Industrial Strategy

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INTRODUCTION

The purpose of this document is to provide the reader with guidance on the operation and calibration of Coriolis flow meters. Coriolis flow meters can be utilised for nearly all applications and have a growing market share in many different industries such as oil & gas, food & beverage, chemicals, and pharmaceuticals amongst others. One of the key advantages of Coriolis flow meters is that they 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 [1] [2] [3]. The exact specification differs by manufacturer and model type. In industry, mass flow measurement is often preferred to volume flow due to mass being independent of the process conditions such as pressure and temperature. Therefore, no correction factors need be applied – and a possible source of error is eliminated.

Although Coriolis flow meters provide a direct mass measurement, it is recognised that Coriolis flow meters can be affected by process conditions. Temperature, pressure and viscosity variations are known to influence the measurement performance of Coriolis flow meters [4] [5] [6] [7] [8] [9] [10] [11].

To minimise these process condition effects, TÜV SÜD National Engineering Laboratory (NEL) advise that the best measurement practice for optimum performance would be to calibrate Coriolis flow meters close to service conditions whenever feasible. NEL have substantial experience obtained from decades of research and calibrations of Coriolis flow meters ranging in size, manufacturer and model. This knowledge has been utilised to create this document which provides relevant, and evidence-based, guidance for the end user with respect to the effects of temperature, pressure and viscosity / Reynolds number on Coriolis flow meters. It also details some of the latest research that NEL is undertaking to improve Coriolis measurements under challenging conditions such as elevated pressure and Liquified Natural Gas (LNG) applications.

INSTALLATION

Most Coriolis manufacturers claim that their Coriolis flow meters are not adversely affected by installation effects [1] [2] [3]. As such, they should not require long lengths of straight pipe work upstream and/or downstream of the device. However, NEL recommend that good measurement practice should be followed. The installation guidance can vary depending on flow tube design and Coriolis manufacturer. If possible, NEL recommend a minimum of 5 diameters of straight pipe upstream and downstream of the device. This minimises any potential stress on the device and allows for the meter to be clamped securely both upstream and downstream.

Although not overly affected by flow profile disturbances, Coriolis meters should not be installed close to valves that will regularly open and close as this can cause pulsations and vibrations in the flow. This has the potential to lead to significant mismeasurement of the mass flow [12]. Whilst not stated in the International Organization for Standardization (ISO) measurement standard for Coriolis meters, NEL recommend that any valve should preferably be installed downstream of the Coriolis device with a minimum of 5 diameters of straight pipework separating the valve and flow meter. Valves located upstream should have at least 10 diameters of straight pipework separating the valve and flow meter.

Coriolis flow meters can be adversely affected by stress applied from the adjoining pipe work, and by vibrations acting on the flow meter. As such, manufacturers specify that their flow meter must be fixed firmly to the pipeline. To achieve this, the adjoining pipe work should be clamped securely both upstream and downstream of the flow meter. Care should be taken to minimise any misalignment and to ensure there is no torsional stress on the meter from the installation.
The fluid pressure drop through the Coriolis flow meter is extremely important and is often the key parameter considered when selecting and installing a Coriolis flow meter. To avoid excessive pressure drop in the system, some end users select a Coriolis flow meter that has a larger bore than the process line size. However, oversized meters are not only more expensive, they would be operating with a larger measurement uncertainty for the application. At low flowrates the fluid velocity in the larger Coriolis device would be at the lower end of the Coriolis flow meter's operating range in comparison to a correctly sized Coriolis (Figure 1). As such, the zero-stability value would adversely influence the measurement performance resulting in a larger measurement uncertainty [13].

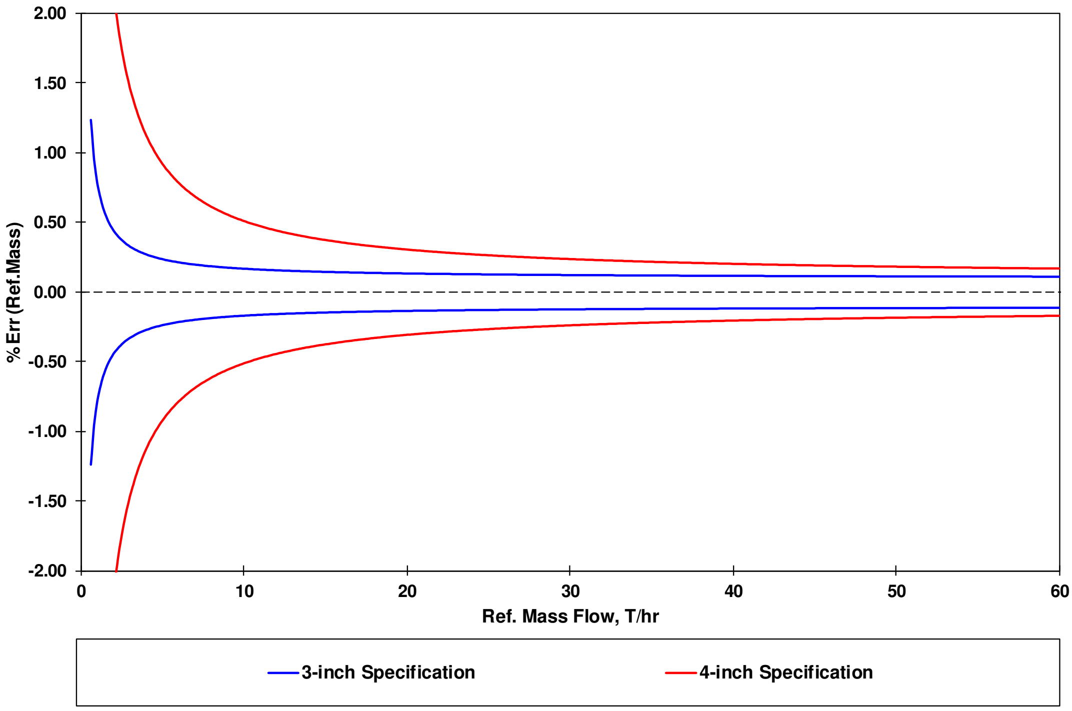

Figure 1. 3-inch & 4-inch Coriolis flow meter specification

ZEROING A CORIOLIS FLOW METER

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 the phase of oscillation of each measuring tube, a mass flowrate can be calculated.

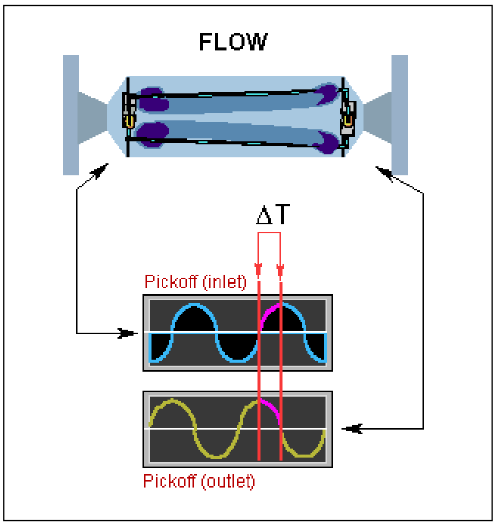

Figure 2. Coriolis flow meter "out of phase".

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 where the time shift caused by the Coriolis force is also small.

To mitigate this, Coriolis devices should 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 being researched by NEL.

Equation (1) details the mass flow calculation deployed by the Coriolis flow meter and the "zero" terms [14].

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

where

Q_m	=	Mass flowrate
CF	=	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 after installation [1] [2] [3]. The zero procedure differs from one manufacturer to another with different specifications and nomenclature used. There is a limit to the value that would constitute an acceptable zero. This also differs by manufacturer, model and meter size.

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. The units for the totalizer can be standardised to allow for a comparison. A typical unit for this check is kg/h as this matches the zero-stability often quoted by the manufacturer. A generic method used by NEL 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 *.
2. Flow through the device at moderate velocities (> 2 m/s) 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 isolating the flow section on the downstream side following site operating procedures. It is beneficial to also have isolation upstream of the flow section.
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 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.

* 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. More details in Section 2.

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 following site operating procedures.

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

$$Q_m = CF \times \Delta t_m \tag{2}$$

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.

SERVICE CONDITIONS

Temperature

Whilst known to be affected by temperature, all Coriolis flow meters have an onboard Resistance Temperature Detector (RTD) and algorithms to correct for temperature. Each Coriolis flow meter is supplied with their own temperature correction factors that are unique to the model type. They have been derived from manufacturer research and development (R&D) at a range of temperatures. NEL research has also confirmed that the uncorrected temperature effect on Coriolis flow meters is linear (Figure 3) [5] [6].

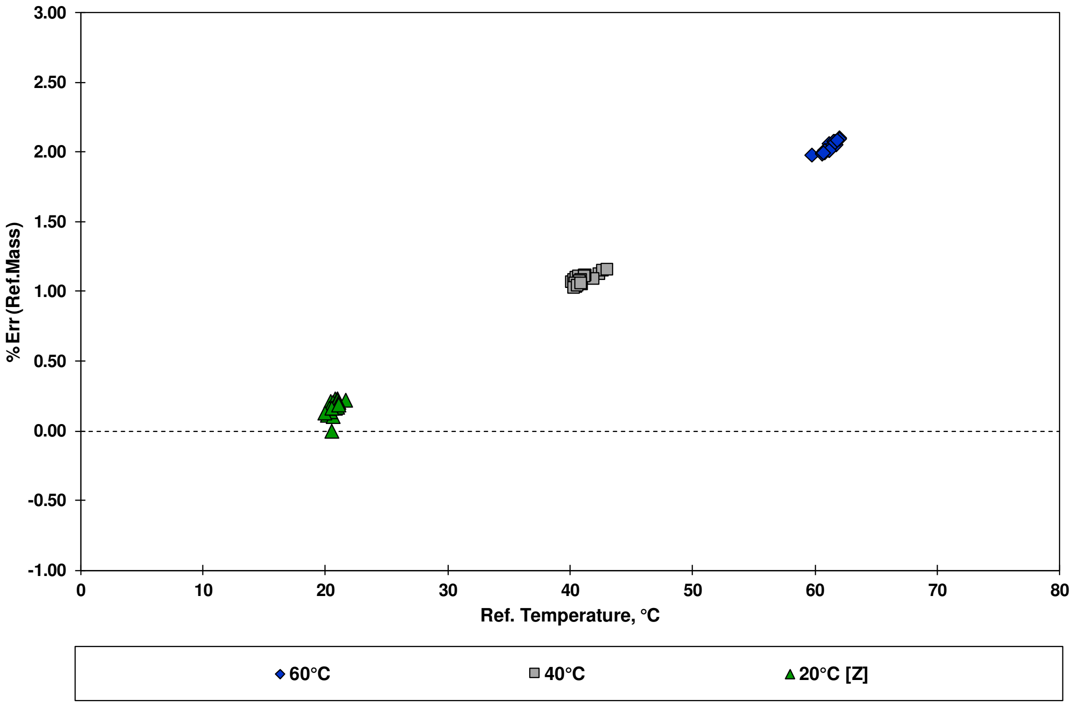

Figure 3. Coriolis meter uncorrected mass flow error when zeroed at 20 °C.

The temperature of the fluid can cause changes in the Coriolis sensor's material elastic properties. As the temperature increases, the flow tubes become less stiff and can potentially over-read the mass flow [15].

To compensate for this effect, the Coriolis flow meter utilises the onboard RTD to automatically correct 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.

The temperature compensation coefficient cannot be easily modified by the end user. 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 NEL 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.

For certain applications, there might not be a suitable calibration facility that can calibrate close to service conditions. For example, regarding LNG applications, transferring an ambient water calibration to cryogenic conditions could produce measurement uncertainties significantly larger than the often quoted 0.1 % specification. In this instance, the end user might select to calibrate their device using water at ambient conditions and deploy it to their LNG service conditions with the caveat that they will encounter a significantly greater measurement uncertainty.

However, this increased measurement uncertainty might be sufficient to meet the end user's requirements. In this instance, cost or availability might be of greater importance. A measurement uncertainty closer to 1 % for the device would be more realistic and acceptable to the end user.

<u>*Pressure*</u>

The validation of pressure compensation coefficients should be a critical consideration for Coriolis flow meters. The pressure of a fluid can affect the elasticity (Young's modulus) of the measurement tubes of a Coriolis flow meter [4]. 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 [4]. For certain Coriolis designs, as the pressure increases the curved tubes stiffen and attempt to straighten to their original tube form (Bourdon Effect) [16].

The pressure effect has been shown to be linear for the numerous Coriolis meters calibrated at NEL at elevated pressure conditions (Figure 4) [7]. They 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 [1] [2] [3].

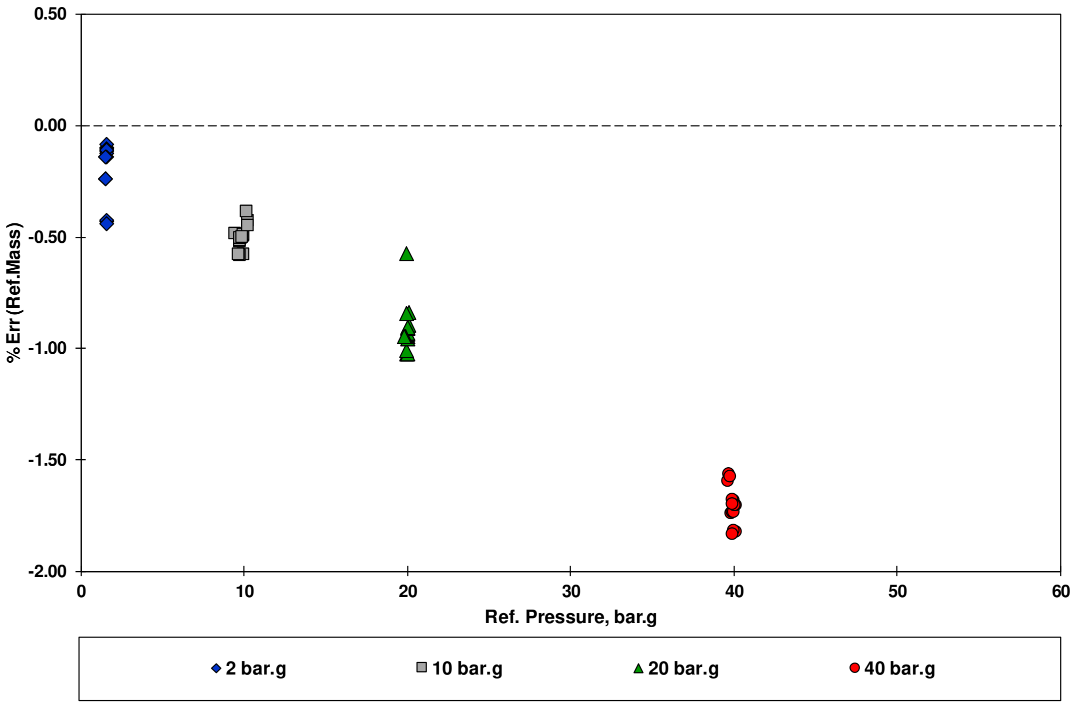

Figure 4. Coriolis meter uncorrected mass flow error (2 to 40 bar.g) vs pressure.

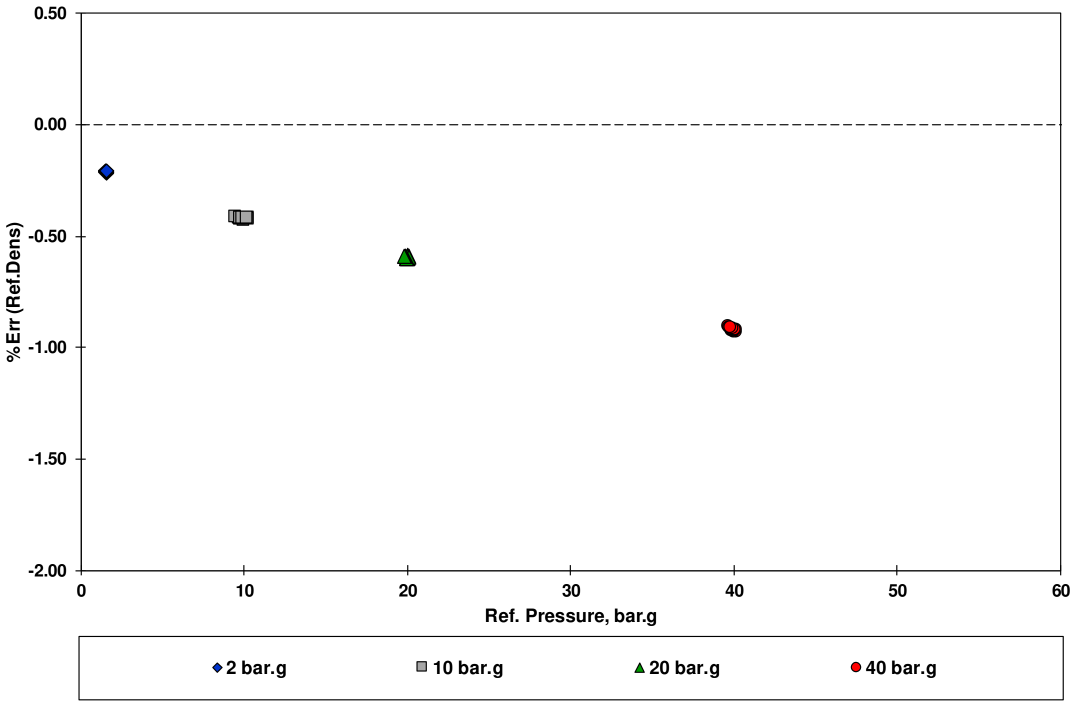

Figure 5. Coriolis meter uncorrected density error (2 to 40 bar.g) vs pressure.

Whilst pressure compensation values are available for Coriolis flow meters, the majority are not fully traceable and have not been derived from independent, accredited flow facilities, such as NEL's. The situation can be further complicated due to the end user not knowing whether a pressure compensation has been applied to the device or not.

NEL recommend that a traceable pressure correction should be used where possible. This would be derived from a calibration at service conditions at an independent, accredited flow laboratory. If the process conditions are stable, 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.* -0.02 % per bar.g), then even a 5 bar.g variance could produce a meter offset of -0.10 % from 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 would vary with the measured service pressure. A calibration procedure recommended by NEL 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 perform an 'as left' calibration.

Viscosity / Re No

Viscosity is a critical parameter in flow measurement. Traditional flow meters such as turbine and positive displacement meters are known to be affected by fluid viscosity [11] [17]. Historically, Coriolis meters have been thought of 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 effects from the velocity profile variations in laminar, turbulent and transitional flow would be negligible.

NEL have conducted significant amounts of research into this challenging area [5] [8] [9] [10] [18]. The results below are for 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 300 cSt) with the trade name "Primol". The results for the light fluid, "Kerosene" at all four viscosities / temperatures are well within the manufacturer specification (Figure 6) with no temperature effect apparent.

Figure 7 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 8. 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. Indeed, a current Coriolis manufacturer has a patented Reynolds Number correction. This has been investigated at NEL as part of an R&D project [11] [19].

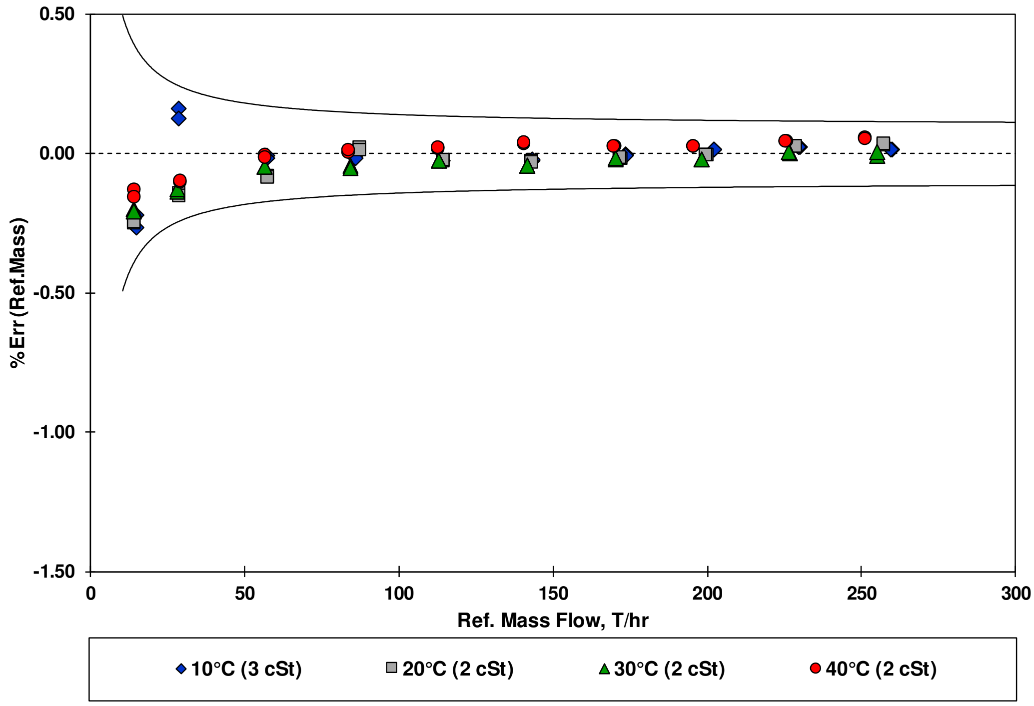

Figure 6. Coriolis meter mass flow (2 to 3 cSt) error.

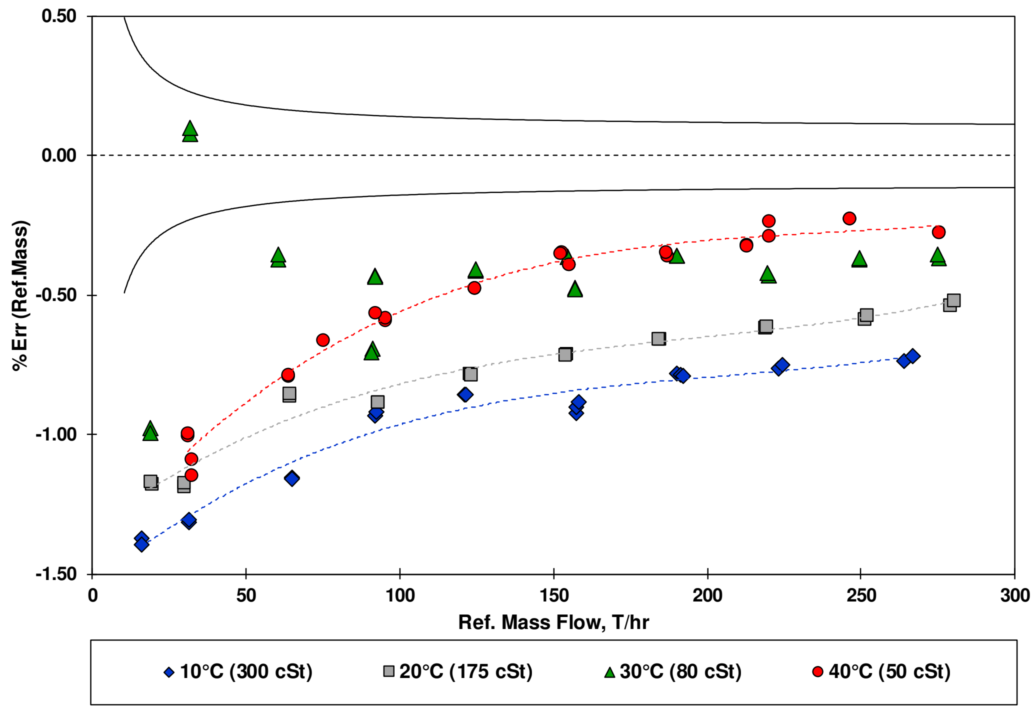

Figure 7. Coriolis meter mass flow (50 to 300 cSt) error.

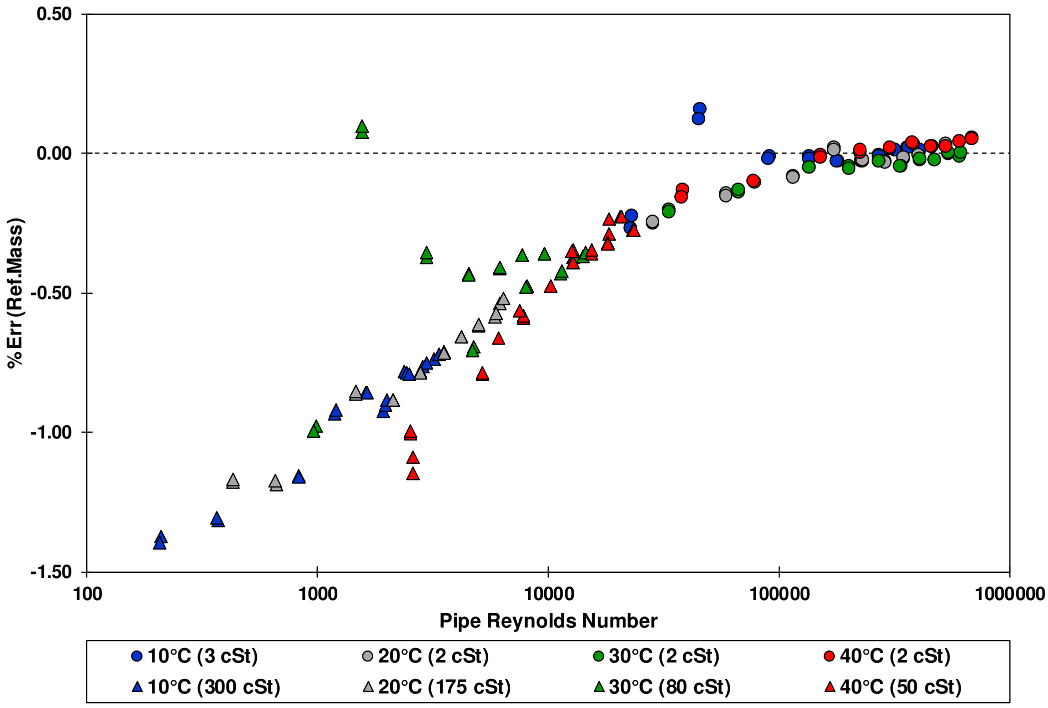

Figure 8. Coriolis meter mass flow (2 to 300 cSt) error vs pipe Reynolds number.

Historically, Coriolis flow meters were not believed to be susceptible to viscosity / Reynolds number effects [11] [18] [20] [21]. Figure 8 clearly illustrated that there is indeed a notable Reynolds number effect for the Coriolis flow meters tested in this experimental programme. There has subsequently been research by universities and also Coriolis flow meter manufacturers into this vital area [20] [21].

An important term for Coriolis flow meters and Reynolds number effects is the "Aspect Ratio", α. It can be defined using Equation (3).

$$\propto = \frac{L}{r} \tag{3}$$

where

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

Whilst there has been research into this area, there are differing opinions on the causation. Kutin *et al.* [20] 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. Tschabold *et al.* [21] 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. These effects were not apparent in the research performed by Kutin *et al.* [20] for all Coriolis meter sizes.

In terms of viscosity effects, 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 would cause deviations greater than 0.5 % (Figure 7). That would mean that the Coriolis device would have deviations approximately five times larger than the water specification of the device.

Correcting for the adverse effects of viscosity / Reynolds number can be challenging. Depending on the manufacturer, the device might apply a Reynolds number correction. A calibration procedure recommended by NEL 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.

CURRENT RESEARCH

NEL are currently undertaking research into the applicability of Coriolis flow meters for the measurement of LNG. Although Coriolis flow meters are excellent devices, the cryogenic temperature (-160 °C) of LNG poses challenges to the validity of the temperature correction algorithms that were developed at elevated temperatures.

While facilities are available for calibrating Coriolis flow meters close to service condition for fluids operating at ambient or elevated temperature and pressure, no such facilities are available for cryogenic fluids apart from one small facility (25 m^3/h) in Europe. However, the flowrate encountered in the LNG industry can be several orders of magnitude higher than 25 m^3/h.

One of the objectives of an existing European Metrology Programme for Innovation and Research (EMPIR-LNGIII) project for LNG is to continue development of an 'economic calibration concept' which transfers calibrations at ambient conditions (water) to cryogenic conditions for both Coriolis and ultrasonic flow meters. The aim of the LNG projects is to achieve measurement uncertainty within 0.5 % for LNG flow. This has been demonstrated successfully in the previous LNGI and LNGII projects for Coriolis flow meters up to 2" in size and validated by the small scale cryogenic facility. In the LNGII project the work has already started to extend the capability of the cryogenic facility to 200 m^3/h and pressure up to 10 bar.g. this allows for validation of the economic calibration concept for flow meters up to 4" in size in the LNGIII project. A feasibility study is already planned to extend the LNG flow to 1000 m^3/h to validate the concept for larger flow meters and at the same time allows flow meters to be calibrated at service conditions when required.

However, a major limitation of this economic calibration concept is that the corrections determined are only valid for that specific meter type and size, rather than broadly applicable. Hence, this process of calibration in water and LNG to determine a correction would need to be performed for every type and size of meter deployed for LNG service.

Another separate project explores pressure effects on Coriolis flow meters using NEL's Elevated Temperature and Pressure (EPAT) facility[†]. The project aim is to provide credible, independent research data that allows end-users of Coriolis flow meters to make informed choices about calibration and operation. For those requiring the best possible uncertainty, EPAT will offer a calibration at the service conditions. For those wishing to use calibrations at near ambient conditions, this research will help to identify the likely errors and mitigation strategies using inbuilt pressure corrections.

To further utilise the high-quality data gathered from Coriolis calibrations at NEL, a software tool has been created that allows online software integration between the NEL EPAT facility data acquisition system and a central

† https://bit.ly/2U2U2yM

database. This database will allow for the traceable experimental data for the effects of pressure and temperature on Coriolis flow meters to be interrogated for the benefit of industry *via* knowledge transfer.

The database will enable experimental data to be filtered, compared and analysed to provide insight into various Coriolis models performance at elevated pressures. As of 2019, the database contains over 25,000 test points and is updated with every calibration completed at NEL. The database will provide industry with conference and journal papers, articles, webinars and presentations on the performance of Coriolis flow meters. The data will be made available for future revisions of the Coriolis measurement standard, ISO 10790:2015 and will ensure it has the latest information and guidance available [22]. Parameters such as temperature, meter size, model type and even manufacturer will be analysed. This will ultimately give greater confidence to the end users of Coriolis metering technology.

FURTHER READING

BS ISO 10790:2015, 'Measurement of fluid flow in closed conduits — Guidance to the selection, installation and use of Coriolis meters', London, BSI

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Report Production

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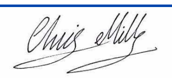
Author(s)	Chris Mills	
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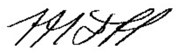
Approved by	Dr Martin Hanton, Technical Director	

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