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# Profiling and Trending of Coriolis Meter Secondary Process Value Drift Due to Ambient Temperature Fluctuations

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**Abstract**—Coriolis mass flow metering technology is widely used within the Oil and Gas industry. There is now an increased focus on utilising the technology’s ability to calculate fluid density in areas such as fluid contamination indication and feedback for process control loops. However, it is common for flow meters of this type to be installed within environments that are subject to severe variations in ambient conditions. One such condition, which this paper seeks to address is the effect that air temperature surrounding the meter body can have on the Coriolis meter’s ability to correctly calculate fluid density, specifically in scenarios where there is a significant differential between the fluid temperature present within the meter internals and the surrounding ambient air temperature. This paper details an experimental program that was carried out at NEL where the ambient temperature surrounding a Coriolis meter was varied in a controlled manner while diagnostic data output from the meter were logged over time. Analysis of the data has allowed for the identification of repeatable drift in both the calculated fluid density and indicated fluid temperature process values output by the metering technology.

## I. INTRODUCTION

Due to advances in data acquisition methods in recent years there is now an increased interest in utilising the diagnostic capabilities of ‘smart transmitters’ that are becoming standard options on commercially available Coriolis meters. References [1], [2] and [3] have summarised within published work the evolution of Coriolis Mass flow metering technology to its current form found in industry today. While modern Coriolis flow meters are capable of outputting over one hundred unique process values, the majority of industries will only log ‘mass flow rate’ as the primary measurement with focus on ‘indicated fluid temperature’ and ‘calculated fluid density’ as the secondary measurement data. The intended use of the secondary variables logged depends very much on the specifics of the installation. For example, a facility which requires

detailed condition monitoring may rely on fluid temperature and density to feed into a process control PID loop, or the facility may be a calibration laboratory and as such will rely on precision measurement data from both the flow meters and their own reference devices as a comparison. In most cases flow metering technology tends to be implemented in heavy industrial environments and as such the technology can be exposed to severe ambient conditions that can have a direct effect on the sensing mechanisms employed by the meter to calculate and output said variables.

The effects of ambient vibration caused by third party facility components have already been extensively researched. Work carried out in [2], [4] and [5] highlight that vibration effects causing data drift in Coriolis meters can be counteracted by implementing appropriate mechanical decoupling for different meter designs. Work carried out by [6] and [7] have focused on velocity profile effects and meter sensitivity to flow conditions internal to the meter, while there has also been research by [8] into the dynamic response of the technology, with respect to fast paced requirements in meter data output and meter response to changing flow conditions. There is a definite gap in knowledge, however, with regards to published data with a focus on targeted experimentation to fully demonstrate the effects of ambient temperature and as such there is not the same level of scientific knowledge that can be used to counteract ambient temperature effects on Coriolis technology. An experimental program in an attempt to better understand zero drift was carried out by [9]. As part of the experimentation, trials were conducted with regards to varying the levels of ambient temperature surrounding a Coriolis meter body. The findings of [9] highlight that meter output values will experience drift during ambient temperature changes, with particular note on variations in ambient air heating patterns producing differing extents of drift. While the work carried out by [9] has indeed shown a quantifiable ambient temperature effect on the Coriolis flow metering technology, the depth of the experiments conducted

does not give a true overview of the potential temperature effects in play: specifically, fluid flow within the meter. In order to conclusively establish the effect of ambient temperature upon the technology it is important to ensure that the experiments conducted simulate the ‘field use’ conditions of the device. Since the experiments conducted by [9] did not make use of a flowing fluid it cannot be conclusively stated that the ambient temperature surrounding the meter did not condition the fluid internal to the meter. Over time the ambient temperature of the air, the meter body temperature and the fluid temperature will reach a thermal equilibrium and as such the ability to separate the temperature effects on the meter internals and processing capabilities becomes far more difficult to conclude.

In an experimental program carried out by [10] to assess the suitability of Coriolis meters for use in a specific metering application, environmental temperature effects were identified as a potential factor in the observed drift in meter k-factor along with other facility/process specific factors. As part of the tests detailed by [10], three Coriolis meters were installed in series within a calibration lab environment and subjected to flowing conditions and ambient air temperature variations. Each meter was individually exposed to an ambient air temperature of approximately 20°C above fluid temperature and meter k-factor variation assessed to determine the extent of ambient effects. It is not stated as to whether the change in air temperature was achieved in an enclosed environment or simply localized to the meter in an open lab space. [10] states that a blower was used to introduce environmental change by blowing warm air. [10] concludes that ambient air temperature caused two out of the three meter’s k-factor to drift out with acceptable limits. However, it should be noted that the investigation into ambient effects was part of a larger study into meter performance and as such the resolution of data regarding ambient effects is limited. Varying the ambient air temperature and trending drift over time for example may have produced a distinctive meter response profile with respect to air fluctuations that could have been used as an installation and meter data interpretation guide for the specific facility setup in question.

Additionally there has been an interest in particular areas of research to allow for the design of ‘intelligent meters’ that are capable of detecting factors that can cause meter output drift [11]. Work carried out in [12] has focused on the sensing mechanisms used within Coriolis meters and how any inaccuracies relating to their deployment in meter design can contribute to meter value drift.

All the work mentioned here has allowed for a greater insight into the operational limitations in Coriolis flow technology, as well as providing potential solutions for the specific sources of error that can cause incorrect values to be produced by the technology. It is this paper’s intention to add a unique data set to this body of work that will allow for a greater understanding into an ambient effect that as of this moment has little conclusive data to allow for corrections or meter technology improvement to be progressed.

The body of work which this paper reports on has been designed with the aim of performing detailed experimentation that ensures that any effects on meter outputs due to ambient air

temperature variation can be quantified, with other temperature effects from external sources accounted for and discounted as the cause of measurement drift.

## II. TEST RIG DESIGN AND LAYOUT

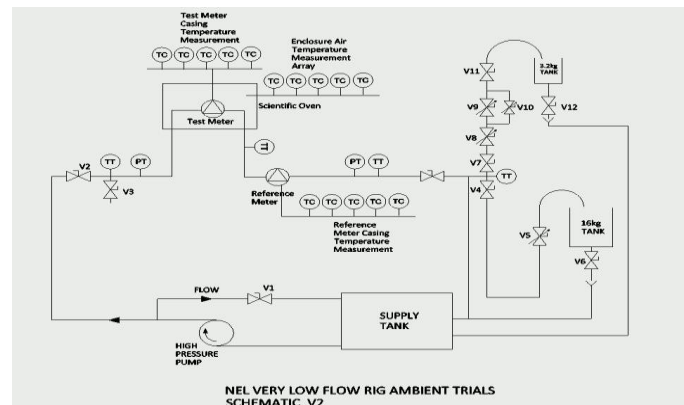


Fig. 1. Diagram of Very Low Flow Facility located at NEL. The facility was operated in the configuration shown in this diagram throughout testing. The data reported in this document is a direct result of the measurements taken from this facility.

The final design of the facility used in the experimental program is shown in Fig. 1. The basic principle of the rig operation is as follows:- Oil is drawn from the supply tank by a circulation pump, from which point the fluid is discharged to the facility test section. The pump installed in the facility is a positive displacement gear pump with a 240V drive motor that operates under the principle of magnetic drive coupling. The pump is also protected by a safety cut off, which allows decoupling from the magnetic drive should it experience unacceptable flow conditions. i.e. dead end flow circuit or high upstream fluid pressure. The facility test section length measures as standard at 700 mm long, however this has been extended to 1500mm to accommodate piping to the additional thermal chamber, required to undertake these ambient temperature trials. In order to ensure that ambient temperature variations can be quantified it was decided that any experimentation conducted should employ the use of a two - meter setup. Both meters were specified and sourced to be of identical meter manufacturer and model. Meter 1, acting as a reference device, would be exposed to stable ambient conditions throughout the experimental test program. Meter 2, designated as the device under test, would be enclosed within a programmable temperature chamber. The data output from both meters can therefore be compared with any deviations in measurement data output from the meters analysed. As shown in Fig. 1 the two flow meters are installed in series, thus ensuring that they are both exposed to the same fluid passing through the internals. The fluid is conditioned to a controlled temperature by the facility heat exchanger circuits within the supply tank, thus ensuring that any potential temperature effects on the fluid due to residency time within the temperature chamber were kept to a minimum. The temperature of the fluid is logged in three strategic locations on the fluid path by calibrated precision platinum resistance

thermometers. The upstream fluid temperature logged is an indication of the fluid temperature after it has passed through the facility conditioning circuits and before it passes through the test meter which is enclosed within the temperature chamber. The mid point temperature is located at the fluid exit point from the temperature chamber and represents the fluid temperature after it has passed through the test meter/temperature chamber, before it enters the reference meter. The third measurement point is located downstream of the reference meter and represents the measured temperature of the fluid as it exists in the reference meter before it returns to the facility storage tank ready for recirculation. By logging the temperature at these three locations we are able to accurately quantify any temperature change in the fluid that has been caused by its presence within the elevated temperature environment and thus can be taken into account when making conclusions on meter process value drift due to ambient temperature variations. The upstream and downstream pressures of the test section were also logged to account for any potential pressure effects.

The internal pipe diameter throughout the facility measured at 8mm. Both the reference and test meter were sized to be 0.5” dual tube ‘U’ shaped Coriolis flow mass flow meters. Meter tube internal diameters measured to be 3mm per tube. Pipe runs directly before and after the temperature chamber were insulated to ensure minimal heat transfer between fluid measuring points. Piping within the temperature chamber was also insulated to ensure fluid temperature conditioning was kept to a minimum while it flowed within the temperature chamber. Heat exchange between the meter body and the fluid while inside the temperature chamber is unavoidable but can be quantified. This will be discussed further in section IV and V.

To gain a deeper understanding of the ambient temperature effects upon the flow meter body a series of thermocouples were fixed to the meter casing of both the reference and test meters as shown in Fig. 2.

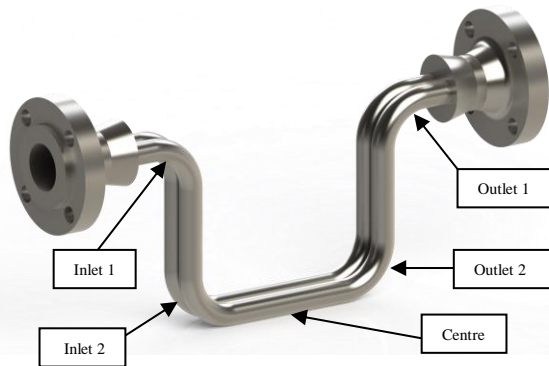


Fig. 2. Location of additional temperature sensors fixed to meter body, to provide data on the temperature profile of the flow meter casing as the surrounding air temperature varies.

As part of this experimental program a Modbus server/client was implemented with the purpose of logging all relevant diagnostic values output by the meters. Within the context of this experiment, diagnostic values refer to process values such as mass flow rate, measured fluid density and fluid temperature

as well as meter internal performance information such as transducer signal performance, internal electronics temperature and error flags. The standard pulse and 4-20mA signals from the meter were also logged by data acquisition hardware standard to NEL. The 4-20mA signal was configured to output the calculated fluid density due to the fact that this is a commonly logged ‘secondary’ output from Coriolis mass flow meters throughout the oil and gas industry.

In order to ensure that the reference meter was exposed to controlled ambient conditions, the facility was setup within a lab space of 4m x 3m x 2.2m.

### III. TESTING AND MATRICES

For all tests performed, the following variables were controlled to remain a constant:

- Fluid Type – Facility filled at beginning of test program with Gas Oil. Once trials in Gas Oil were completed, the facility was flushed out and test fluid was replaced with water.
- Fluid Temperature – Controlled by facility heat exchanger conditioning circuits
- Room Temperature – Air Conditioning
- Upstream Pressure – Throttle and bypass valves
- Downstream Pressure - Throttle and bypass valves

The three primary variables which were adjusted were:

- Temperature chamber air temperature – Chamber programmable interface
- Rate of temperature increase within temperature chamber – Chamber programmable interface
- Fluid flow rate – Recirculatory Bypass valve

The aim of varying the air temperature within the temperature chamber was to simulate ambient temperature swings that may be experienced in real world situations e.g. process plant temperature swings due to third party equipment or uncontrollable natural phenomena such as direct sunlight. A maximum value of 65°C was decided upon due to the recommended operating temperature for the electronics components of the meter being ~70°C. The aim behind varying the rate of temperature increase was to acquire a data set which could provide insight as to the time taken for thermal interactions between the fluid, meter casing and air to reach a continued balance. Varying the fluid flow rate was performed with the aim of targeting the fluid temperature effect on the internals of the meter, as well as assessing the meter internals and casing temperature effect on the fluid temperature. In real world process conditions it may be common for fluid flow rate to vary frequently depending on the specifics of the application, and as such any ambient temperature effects that are amplified by variations in fluid flow through the meter must be accounted for. A flow rate of 130kg/hr was decided upon as the maximum flow rate based on data obtained during rig commissioning. This showed that 130 kg/hr was the optimum flow rate that the rig could achieve

in the configuration detailed in II without introducing cavitation. The decision to conduct the trials with two different fluids was taken primarily due to the differing thermodynamic properties between Gas Oil and Water. By running the test program of Gas Oil and then repeating the conditions for water this allows for any additional effects caused by the different fluid properties to be observed and quantified.

Before any data logging commenced the fluid was circulated for at least one hour within the facility to allow for steady state conditions to be reached with regards to fluid temperature, meter casing and internal temperature. The chamber door was opened to allow all tests to begin with a balanced ambient temperature between both the reference and test meter. Once steady state conditions were achieved, test point collection was commenced. For the initial fifteen minutes of data logging the rig would remain at steady state conditions to allow for an initial reference point before ambient conditions were altered as part of the test matrix. After this point, the chamber door was closed and an ambient temperature setpoint for the test meter was set. The table shown in Fig. 3 summarises the baseline targets that the rig was set to achieve for each individual test point. During selected test points (TPs 5, 9 & 14) a reduction of flow by 50% was initiated once the final temperature setpoint for ambient air within the temperature closure had been reached. This reduction in flow was performed with the aim of observing further temperature effects due to the temperature differential between the fluid and the air surrounding the meter. The rate of temperature increase was not varied within individual test point collections. Rate of temperature was therefore a fixed variable per test point to ensure consistency.

For the trials in which Gas Oil was present within the facility, three key test points were carried out, the only variable in each being rate of ambient temperature change as Fig. 3 summarises. As an additional check, once these key test points were completed, the meters positions were swapped i.e. ‘Reference Meter’ was installed in temperature enclosure and the ‘Test Meter’ now installed in controlled ambient conditions external to the meter. This was done with the express aim of ensuring that any drift that had been observed during the initial test points for the fluid were not specific to one single meter. Reversing the positions and repeating the experiments under the same conditions ensured that drift was consistent within this particular meter design and not due to a manufacturing fault in one specific case.

This process was repeated for water. It should be noted that for water an additional rate of ambient temperature change parameter was added to the test matrix. This was due to the fact that during testing it was observed that with water present within the meter internals, the time taken for the process values to reach steady state conditions after an ambient temperature change was greater than the time already observed with Gas Oil. The addition of this parameter merely ensures that all possible data were captured and ensures that the fluid effects on the meter drift as a result of ambient temperature change are fully captured.

Test Point No.	Fluid Name	Fluid Flow Rate During Test Meter Ambient Heating (Kg/hr)	Initial Test Meter Air Temperature (°C)	Final Test Meter Air Temperature (°C)	Rate of Enclosure Air Temperature Change (°C)	Initial Ref Meter Air Temperature (°C)	Final Ref Meter Air Temperature (°C)	Fluid Temperature Setpoint (°C)	Test Point Duration (including settling times) (Hrs)	Comments
1	Gas Oil	130	20	65	2/15 mins	20	20	20	8	Ref and Test Initial position
2	Gas Oil	130	20	65	5/15 mins	20	20	20	8	Ref and Test Initial position
3	Gas Oil	130	20	65	8/15 mins	20	20	20	6	Ref and Test Initial position
4	Gas Oil	130	20	65	5/15 mins	20	20	20	8	Ref and Test swapped
5	Gas Oil	130	20	65	2/15 mins	20	20	20	8	Ref and Test swapped
6	Gas Oil	130	20	65	8/15 mins	20	20	20	6	Ref and Test swapped
7	Water	130	20	65	2/15 mins	20	20	20	8	Ref and Test Initial position
8	Water	130	20	65	5/15 mins	20	20	20	8	Ref and Test Initial position
9	Water	130	20	65	8/15 mins	20	20	20	6	Ref and Test Initial position
10	Water	130	20	65	2/30 mins	20	20	20	9	Ref and Test swapped
11	Water	130	20	65	2/30 mins	20	20	20	9	Ref and Test swapped
12	Water	130	20	65	2/15 mins	20	20	20	8	Ref and Test swapped
13	Water	130	20	65	5/15 mins	20	20	20	8	Ref and Test swapped
14	Water	130	20	65	8/15 mins	20	20	20	6	Ref and Test swapped

Fig. 3. Summary table of test matrix steady state/Temperature change target parameters.

#### IV. RESULTS

The main focus of this experimental program was to identify the extent of drift that can be caused by ambient air temperature swings in a small bore meter’s surrounding environment. Review of the Modbus and analog values logged by the custom data acquisition program developed for this project have highlighted that the two key secondary variables of interest (fluid temperature and density) are indeed adversely affected. In order to effectively summarise the impact of ambient temperature and the knock on effect throughout the meter’s process output, each individual process parameter will be reported upon separately here. Due to the number of test points taken, a selection of trends produced from the data logged can be viewed in the following figures. The trends and extent of drift observed were shown to be repeatable across all test points.

##### A. Indicated Fluid Temperature

The ‘indicated fluid temperature’ value reported by a Coriolis meter is determined by a Platinum Resistance Thermometer fixed to the pipe wall of the U tube. Due to the fact that this sensor is not in direct contact with the fluid, the temperature value output by the flow transmitter is based on the measured pipe wall temperature.

The experimental results indicate that ‘indicated fluid temperature’ is susceptible to drift and can be directly trended along with the change in air temperature within the temperature enclosure. Fig. 4 highlights this effect and is a graphical representation of the conditions of Test point 1 detailed in Fig. 3.

Fig. 4 shows a direct relationship between the stepped increase of the air temperature within the enclosure over time and the continued drift of the indicated fluid temperature as reported by the ‘test meter’ installed within the temperature enclosure. Test meter indicated fluid temperature increased from 19°C to 25.5°C over the test, whereas the actual fluid temperature only increased from 19.00°C to 21.5°C. The time delay in which the drift due to ambient air temperature increase can be observed is minimal as demonstrated by the first fifteen minutes trended in Fig. 4. As stated in III, the facility was allowed to reach stable conditions for 1 hour before test point logging commenced. The first fifteen minutes of logged data reflect these steady state conditions. There is a

clear increase in test meter indicated fluid temperature that trends with the time in which the enclosure temperature was increased to 25°C.

As a direct comparison, Fig. 4 also shows that the room ambient air temperature that surrounds the reference test meter remains constant. The actual fluid temperature shows a gradual drift throughout the test point of 19.57°C – 21.02°C. This minor increase can be explained by the gradual increase in fluid temperature due to the heat transfer effect of the fluid passing through the pumps throughout the prolonged test point collection time. The indicated reference meter fluid temperature follows this ‘pump heating’ trend.

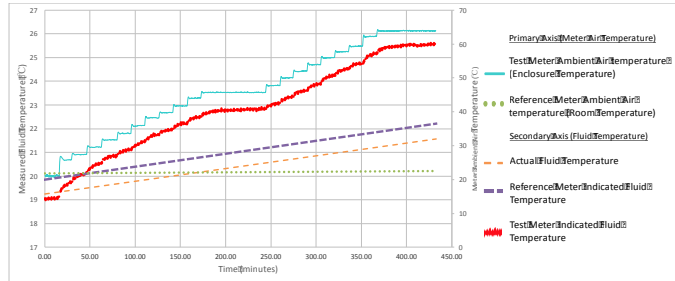


Fig. 4. Observed Test meter ‘indicated fluid temperature’ shift with stepped increase in ambient temperature. Gradual increase of reference meter ‘indicated fluid temperature’ and ‘actual fluid temperature’ due to pump heat transfer also plotted with constant room ambient air temperature.

**B. Calculated Fluid Density**

The data collected as part of this test program also show that there is a significant drift in the calculated fluid density of the meter as a result of the stepped increase in ambient air temperature surrounding the meter in the test enclosure. The data shown in Fig. 5 highlights one such trend observed in Test point 1. There is a clear correlation between the rate of temperature change in air surrounding the test meter and the observed shift in calculated fluid density reported by the test meter. When compared to the calculated fluid density of the reference meter which, while showing drift consistent with the previously described pump heating effect, remains constant and in keeping with the expected fluid properties of Gas Oil.

It should be noted however that the calibrated fluid properties of the Gas Oil used in this test program show that density value drift due to a measured temperature value of 25.5°C should only cause a decrease in fluid density of 4.3 kg/m<sup>3</sup>. The meter however reports a decrease of 15.3 kg/m<sup>3</sup>. Since the trials conducted have been done so from an ‘end user’ perspective i.e. with no access to manufacturer patents, meter internals or processor compensations and algorithms, no further concrete conclusion can be drawn as to the nature of this unexpected drift without gaining access to these parameters. From industry experience and knowledge it is known that the meter manufacturers will make use of internal temperature sensors embedded in the casing of the meter in an attempt to compensate for the effects reported on.

The temperature difference that the reference meter shows across the test is 2.5°C, which as previously stated is consistent with the change in measured fluid temperature due to heating effect of the pumps and not due to ambient

temperature effects. The drift in calculated fluid density as reported by the reference meter is consistent with the expected shift due to temperature effects on this type of fluid.

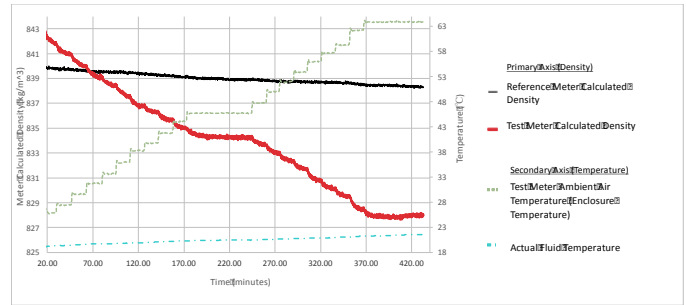


Fig. 5. Observed test meter ‘calculated fluid density’ shift with stepped increase in ambient air temperature plotted. Fluid temperature shown on plot with the intention of giving an indication of real fluid temperature effects during testing.

**C. Other Observations – The Heat Exchanger Effect**

A targeted experiment into the ‘cooling’ effect that the liquid has on the internals due to the temperature differential between fluid temperature and ambient air temperature within the enclosure was conducted once the data from the test matrix shown in Fig. 3 had been reviewed. Fig. 6 summarises the temperature data collected. The facility was allowed to achieve steady state conditions. Once achieved, the flow rate of liquid passing through the meter was reduced by 50% from 130 kg/hr to 65kg/hr while all other variables were controlled to remain constant. This reduction of flow rate caused a detectable drift in indicated fluid temperature causing it to increase by a further 1°C. There was also a detectable increase in actual fluid temperature and indicated fluid temperature as reported by the reference meter. The flow rate was then increased to the original value and, as Fig. 6 shows, the test meter indicated fluid temperature drops back to within the original steady state value. Again there is a detectable shift in actual fluid temperature and reference meter indicated fluid temperature. As a final check the fluid flow through both meters was stopped instantly by switching off the circulation pump. Fig. 6 shows an immediate rise in indicated fluid temperature from the test meter inside the enclosure and begins to converge on the ambient air temperature surrounding the test meter within 30 minutes of stopping the flow rate.

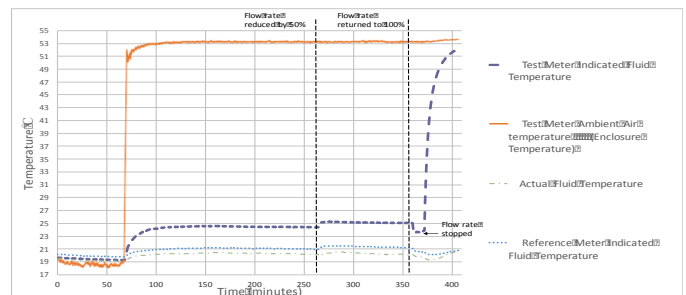


Fig. 6. Effect on indicated fluid temperature and actual fluid temperature from varying the flow rate through both the test and reference meter

The effect demonstrated in Fig. 6 can be further analysed by cross referencing with the data shown in Fig. 7, which shows the values obtained from the thermocouples attached to the test meter body as detailed by Fig. 2. The data was gathered during the same test run as the data shown in Fig. 6. From this graph we can determine how the meter casing is affected by the temperature of the fluid within the meter internal and the ambient air surrounding the meter. The thermocouples located at locations Inlet 2, Centre and Outlet 2 follow the trend of the ambient air temperature increase within the temperature enclosure. However the thermocouples at locations Inlet 1 and Outlet 1 read a value of 35°C at steady state conditions. When the flow rate was reduced in the manner already described, the same trend as observed in Fig. 6 can be observed in Fig. 7, but at elevated temperatures consistent with the meter casing temperatures at those locations. Similarly, when the flow rate was briefly increased to the originally value and then ultimately stopped similar trends to Fig. 6 can be observed here.

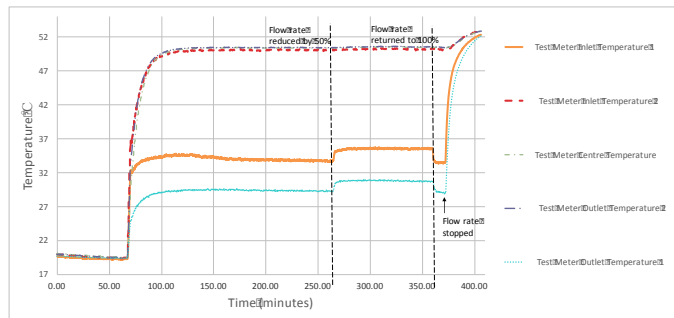


Fig. 7. Combination temperature effect on meter casing from varying fluid flow rate and increasing ambient air temperature

An additional test point was also logged to establish the extent of density drift with the combined effects of high ambient air temperatures and fluctuating flow rate. In this instance the flow rate was again reduced from 130 kg/hr to 65 kg/hr once an air temperature of 65°C surrounding the test meter had been established over 3 hours. The trend shown in Fig. 8 clearly shows a drift in density due to increased ambient air temperature as already demonstrated in section B. A further drift in meter calculated density of 2 kg/m<sup>3</sup> is shown to occur when the flow rate is reduced. When the flow rate is returned to 130 kg/hr the density value immediately begins to recover to the density value previously established at high ambient temperature.

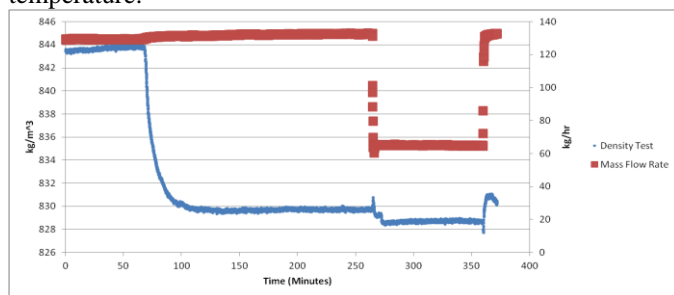


Fig. 8. Combination temperature effect on test meter ‘calculated fluid density’ from varying fluid flow rate and increasing ambient air temperature

D. Mass Flow Rate

Since the primary function of the Coriolis meters under investigation is to measure mass flow rate, the performance of said process value with respect to ambient temperature change was also analysed. Fig. 9 shows that for the ambient conditions set for Test point 1, the mass flow rate process value is not affected in the same manner as indicated fluid temperature and calculated fluid density. The mass flow rate is shown to increase over the course of the test point however the increase in flow rate is also detected by the reference meter as shown in Fig. 10. The pattern of mass flow rate increase is shown to be consistent across both meters and is due to the change in physical properties of the test fluid over the course of the test point due to fluid heating.

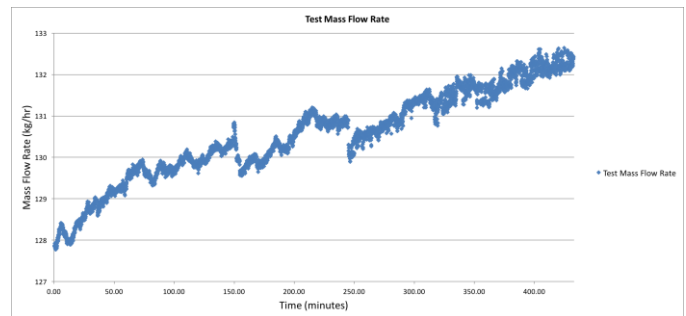


Fig. 9. Observed test meter mass flow rate during test point 1.

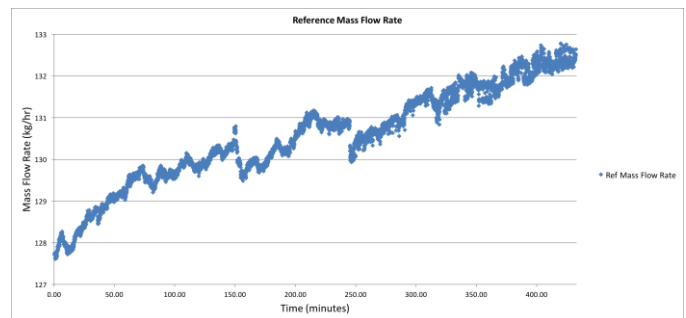


Fig. 10. Observed reference meter mass flow rate during test point 1.

There is however a notable shift in the offset between the reference and test meter. After zeroing both meters before beginning Test point 1, the ‘test meter’ indicated a mass flow rate that was 0.1kg/hr greater than the reference meter. However, by the end of Test point 1 this offset shifted with ‘test meter’ reading 0.1kg/hr less than the reference meter. Fig. 11 shows the drift in ‘reference meter’ mass flow rate vs ‘test meter’ mass flow rate throughout the test point. This trend demonstrates a similar pattern to the drift observed in calculated fluid density and indicated temperature.

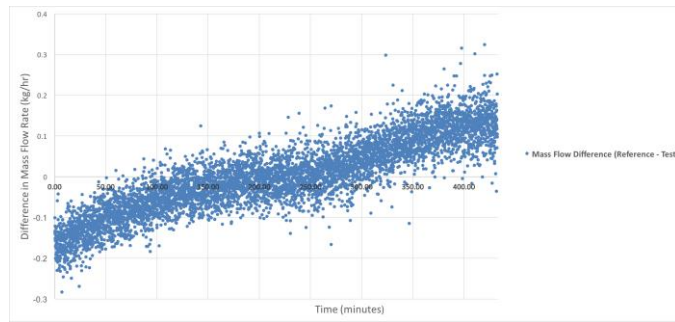


Fig. 11. Difference between reference meter mass flow rate and test meter mass flow rate process values observed during test point 1. Drift pattern that corresponds to test meter ambient air heating pattern visible.

## V. RESULTS DISCUSSION AND CLARIFICATION

The results obtained have provided a deeper insight into the direct impact ambient temperature variation can have on Coriolis technology, specifically in low flow, small bore applications. However it should be noted that the data reported on is relevant to a specific meter manufacturer and model. In order to obtain a data set that is more representative of the potential effects in installations utilising meters of this size, the test program should be repeated with a different manufacturer and model type of Coriolis flow meter. To ensure consistency the meter should have comparable dimensions to the meter used in the above test program. It should also be noted that the extent of the drift observed will be governed by the physical dimensions of the measuring tubes, which are specific to the make and model of meter used in this test program. Since this test program has focused on a small bore Coriolis meter, the effect of ambient temperature demonstrated would differ if this experiment were to be repeated on a meter designed for higher flow rates with larger flow tube and an overall greater mass of construction material.

The additional observation of the heat exchanger effect, reported on in C of section IV requires further targeted experimentation with a higher resolution of fluid flow rate variation and ambient temperature set points. The locations of Inlet 1 and Outlet 1 on the test meter show trends which are comparable with the indicated test meter temperature drift, highlighting that the effect of ambient temperature on the meter casing is significant. The observed increase in actual fluid temperature when the flow rate is reduced is also significant. Due to the increased residency time of the fluid within the test meter, which as indicated by the thermocouples has a casing temperature significantly different to the fluid temperature present within the meter, it is likely that the fluid is picking up heat from the meter.

As described in section B of IV the calculated fluid density output by the test meter drifted by a greater amount than expected. Further research targeting the physical stress imparted on the construction materials of a Coriolis flow meter of this size due to elevated ambient temperature should be considered going forward.

## VI. CONCLUSIONS

The data gathered as part of this particular test program show that there is a quantifiable drift in Coriolis flow meter output when the technology is exposed to significant increases in ambient temperature. The drift observed in the 'indicated fluid temperature' and 'calculated fluid density' process values is valuable information and should be taken into account when designing control systems for low flow process loops, which make use of Coriolis mass flow meters of comparable dimensions to the those reported upon within this document.

Secondary observations relating to the greater than expected shift in the calculated density output by the test meter have shown that the ambient temperature effect on Coriolis meters is a complex phenomenon that cannot simply be corrected for by predicting temperature transmitter error and applying a correction to the resultant density calculation. This highlights the need for manufacturer support in future testing to allow for unknown factors such as manufacturer specific correction algorithms, mechanical specifics in meter design and temperature sensing devices mounting and use in correction factors to be accounted for. Further work must now be undertaken with a targeted experimental program aimed at identifying and quantifying the contributing factors to the observed density shift when the meter is exposed to high ambient temperatures. This should encompass targeted experimentation and potentially finite element analysis of the meter body to allow for a better understanding on the temperature effect on the metals and sensor components at specific points on the meter body so that more efficient correction methods can be developed.

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