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Technical Paper

Coriolis Density Error – Targeting Ambient Temperature Fluctuation and the Development of a New Temperature Compensation Model

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1 Introduction

This paper details the experimentation, results and output of a 4-year doctorate research project, the objective of which was to develop new ambient air temperature compensation techniques for calculating fluid density on a Coriolis flow meter. The primary driver for this research topic is the recent increase in interest from end users with regards to utilising the density value from Coriolis meters for applications such as fuel bunkering, condition based monitoring and live fluid property determination. A targeted experimentation protocol was developed with input from manufacturers and end users, resulting in a facility build which allowed for realistic ambient temperature variations in the surrounding environment of the meter to be simulated at flowing conditions. As a result of this research it was discovered that the error imparted on the density calculation by ambient temperature can be live corrected by repurposing existing diagnostic measurements on the device transmitter. Therefore, using the high-resolution data sets obtained during testing, a new correction model was developed and validated by way of blind testing. The new model is shown to work on both ageing Coriolis devices currently installed in the field as well as new generation devices currently in the prototype stage.

2 Background

The evolution of Coriolis metering technology has been well documented and summarised by [1], [2] and [3]. While differing makes and models are available commercially, the general design consists of a single or dual flow tube, manufactured in a straight or curved configuration. The flow tubes are mechanically driven to oscillate at their natural frequency and controlled via an electronic transmitter containing manufacturer specific control and calculation algorithms as well as temperature compensation coefficients. Displacement or velocity sensors located upstream and downstream of the centre of flow tubes are used to determine the extent of Coriolis force exerting twist on the flow tubes. The time delay measured by these sensors is proportional to the mass flow rate passing through the meter. If no mass flow is present there will be no Coriolis force present, and therefore no time delay is detected between the upstream and downstream sensors.

Fig. 1 – Typical Coriolis Mass Flow Meter Structure

As a secondary output, a Coriolis meter is also capable of determining the density of the fluid present within its internals. This process value is calculated based on a temperature corrected period of the flow tubes and is broadly defined in [4].

Research into Coriolis meter 'zero drift' [5] highlighted ambient temperature variation as a contributing factor in the author's results. When the suitability of Coriolis technology was assessed for a specific industrial application [6], it was observed that the ambient air fluctuations introduced into the system by the research team caused a detectable drift in the meter k-factor.

With respect to the meter transmitter, research in the past has focused on the creation of a self-validating sensor (SEVA) [7], capable of fault detection and data correction to ensure measurement quality is upheld.

This research programme described in this paper was undertaken with the goal of targeting the density output of Coriolis meters, assessing the parameter's response with respect to ambient temperature variation and implementing live automated correction to any resulting calculated density drift via the meter transmitter.

The first phase of this project's experimentation proved that ambient air temperature fluctuation can cause fluid density calculation errors on commercially available meters [8]. The results were presented to a Coriolis manufacturer and, as a result of this, access was granted to confidential meter design information to allow development of an intelligent temperature correction model that significantly reduces these errors. The following goals were identified:

- The correction model should be capable of detecting calculated fluid density drift due to ambient air temperature change.
- The correction model should be able to account for the possibility of differing fluid properties present within the meter and their associated effect on the thermal balance of the system.

The results of a new model, capable of correcting for errors induced by ambient air temperature were published in [9] and [10]. This paper represents a direct continuation of these works.

The importance of correct measurement and interpretation of data output from flow metering technologies is key to production forecasting, custody transfer and fiscal metering as highlighted in research conducted by [11] and [12].

3 Test Design and Previous Results Summary

The experimental setup used to produce the results described in this paper has been previously described in detail within [8], [9] and [10]. For the purposes of this paper, a summary of the key components of the test rig setup is described in this section.

3.1 Facility Layout and Equipment

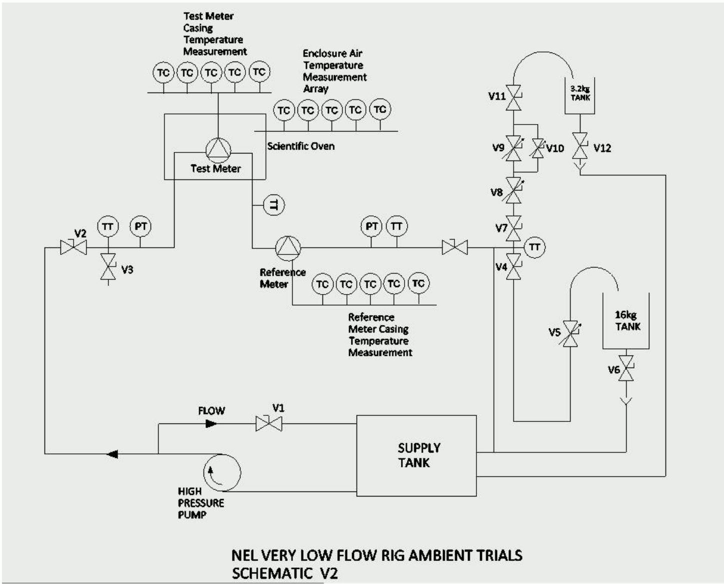


Fig. 2 – Facility setup and Instrumentation Overview

NEL's 'Very Low Flow Facility' (Fig. 2) was modified to allow the piping of the test section to enter and exit a programmable oven. Within the oven, the meter under test (a ¼", dual curved tube Coriolis meter) was installed and connected to the incoming and outgoing test section pipes. Immediately downstream of the test meter/oven an identical Coriolis meter (the 'reference' meter) was installed in series at a controlled ambient room temperature. Reference PRTs were installed upstream and downstream of the test section as well as at the fluid exit point of the oven to ensure that fluid properties were not altered due to heat exchange from the circulation pump, the oven or the test meter body at an elevated temperature. Fluid temperature variations throughout the facility were monitored and their overall impact on the test data assessed.

Access was granted by the manufacturer to the raw uncorrected process values as well as the meter specific correction algorithms which are implemented in the transmitter unit. The correction algorithms were deactivated on both the reference and test meter during data collection so as to log only the raw process values. The correction algorithms were then applied to the data post testing in the data analysis phase.

The fluid properties used during testing were analysed in house by NEL's UKAS accredited fluid property analysis lab.

3.2 Temperature Compensation Models

The experimental setup and resulting data described in section 3.1 allowed for a new temperature compensation method to be developed and validated, the initial results of which were reported in [9] and [10]. A summary of the new method is described below. Due to a non-disclosure agreement between NEL and the project partner, the specific algorithm structures cannot be presented in full. However, given that fluid density calculations performed by Coriolis technology is described in ISO 10790 [4], the key weaknesses of the existing model as well as the modifications resulting from this research can be discussed in a generalised form.

3.2.1 Manufacturer Method and Inherent Weaknesses

To compensate for temperature effects on the fluid density output of Coriolis meters, one must account for the associated physical effects of Young's modulus on the flow tubes and therefore the effect on the harmonic period of the structure from which fluid density is derived. However, the focus of the manufacturer's existing compensation method is largely specific to fluid temperature effects and does not account for other sources of temperature.

Harmonic period compensation coefficients are determined by the manufacturer during initial meter calibration. These coefficients are derived using water and are used throughout the device's duration of service unless specifically altered by a trained technician.

The period is a live process value, dependent on the fluid properties present within the meter internals as well as the physical properties of Coriolis sensing tube, both of which are dependent on the thermal interactions that can occur between the ambient air, meter body temperature and fluid temperature. Therefore, temperature sensors on the meter body are used to determine live temperature conditions, which are subsequently compared to reference temperature values per sensor, stored on the meter's electronic transmitter.

These reference values are representative of the conditions observed during initial factory calibration and coefficient generation. As such, the effectiveness of the compensation equation reduces when the difference between the live temperature reading deviates from the reference temperature conditions as well as when the fluid properties deviate from water.

Due to the placing of the sensors on the meter body which feed the current compensation algorithm, the effects of ambient temperature and fluid temperature are not evenly detected. Some sensors are more sensitive to air temperature and meter body variations while others do accurately infer fluid temperature. This was demonstrated experimentally in [9] and [10].

A generalised summary of the manufacturer's temperature compensation algorithm structure is shown below in Fig. 3.

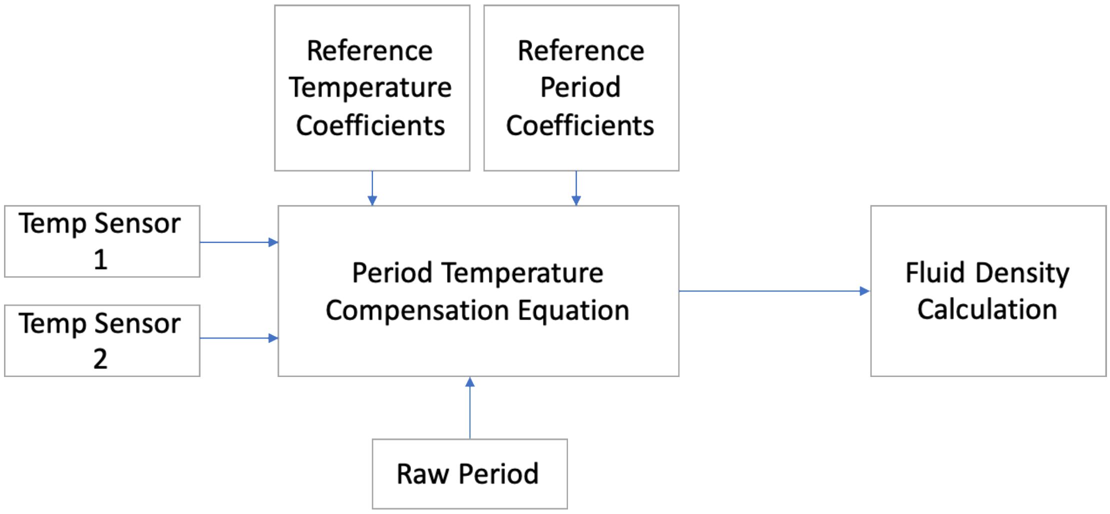


Fig. 3 – Summary of the exisiting manufacturer's temperature compensation structure

3.2.2 New method for fluid density calculation temperature compensation

The sensing imbalance described in 3.2.1 is a disadvantage to the correction algorithm in its current form. However, by repurposing the temperature sensors which showed higher sensitivity to air temperature changes, a new automated temperature correction mechanism was created. The new method was developed around the following assumptions: -

- There could be no change to the manufacturing process of the physical device.
- There could be no change to the initial calibration procedures performed by the manufacturer and resulting data structures.
- The new method should be applicable to existing devices in the field and new build devices.

The new correction method contains a check on the differential between the temperature sensors that were shown to correctly infer fluid temperature and the temperature sensors shown to be influenced by air temperature per processor scan cycle. An additional coefficient 'X' was also added to the routine to allow for fluid property tuning.

The addition of a check on the differential between the temperature sensors increases the robustness of the equation in operating conditions which deviate from the initial calibration conditions. The use of a fluid property coefficient 'X' within the algorithm imbues the system with an awareness of the specific fluid properties for which it is being deployed and therefore enables configuration of the equation for use with fluids that differ from water.

A summary of the new temperature compensation model's structure is shown below in Fig. 4.

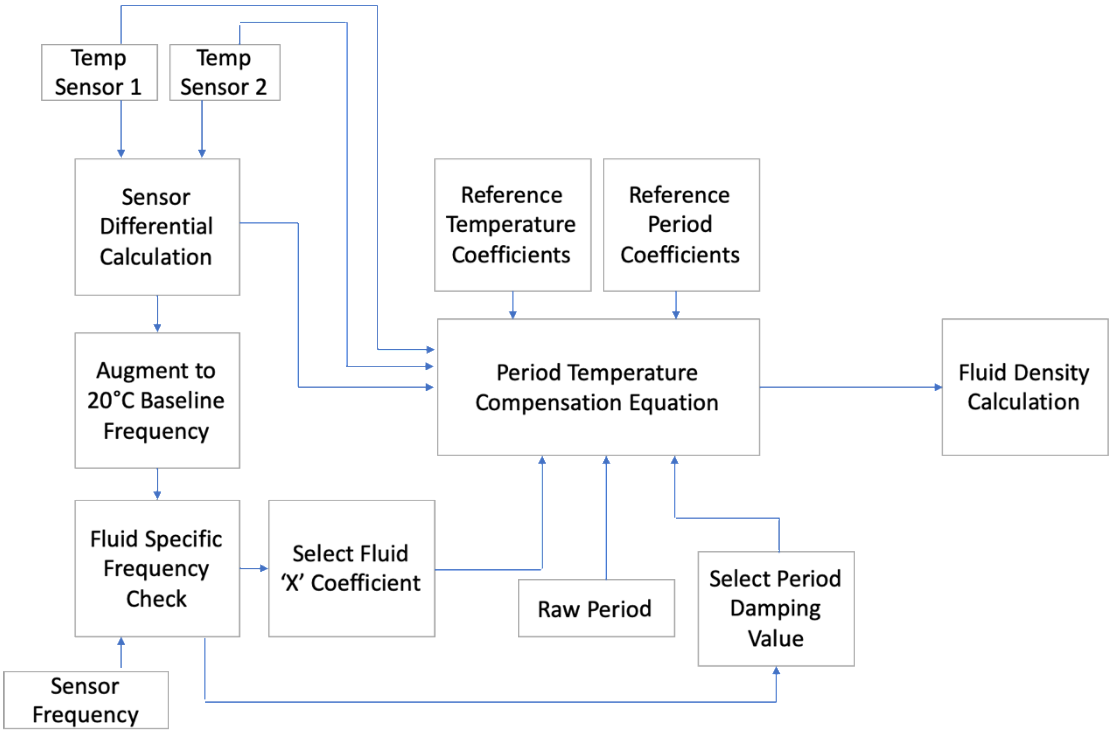


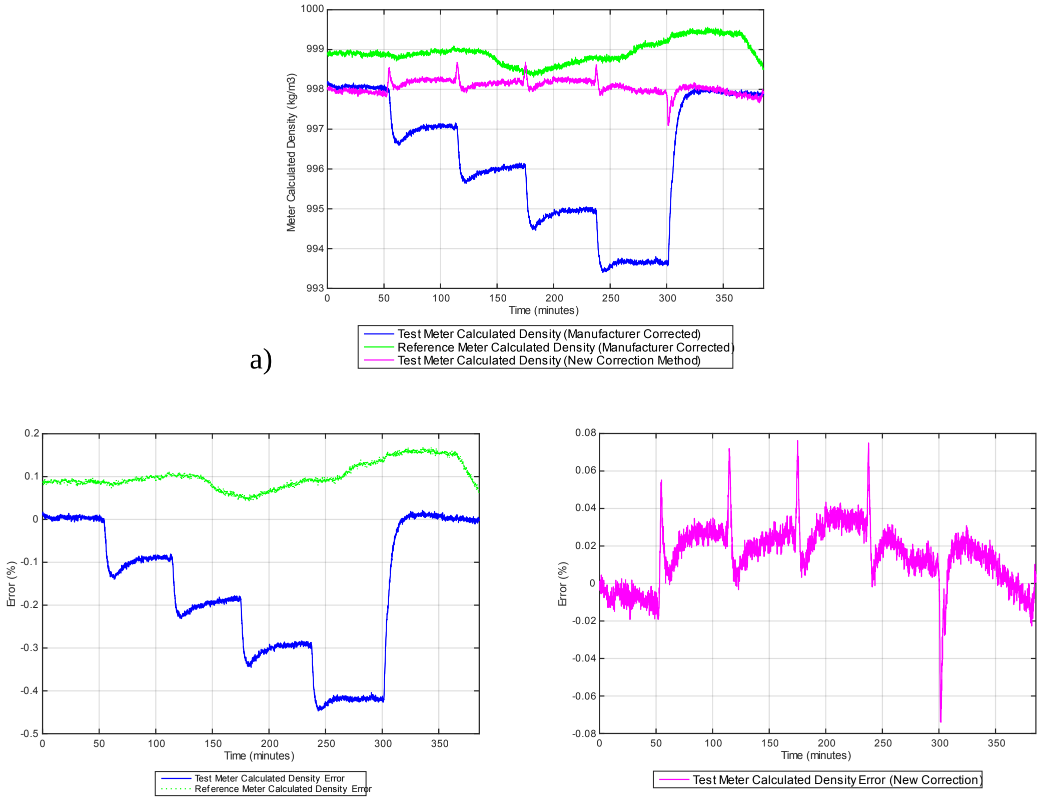
Fig. 4 – Summary of the new temperature compensation model structure

3.2.3 Manufacturer Method vs New Method Results

Figures 5 and 6 summarise the performance of the existing manufacturer model vs the new correction model at the following process conditions:-

- Steady fluid flow rate
- Stable fluid temperature
- Test meter ambient air temperature increased by 10°C every 1 hour.

Fig. 5 shows that, with water present in the system, the manufacturer method produced an error of -0.4% with respect to known fluid density. The new correction method is able to reduce this error to a temporary value of +0.08% during each air temperature increase (referred to hereafter as the temperature transition region).

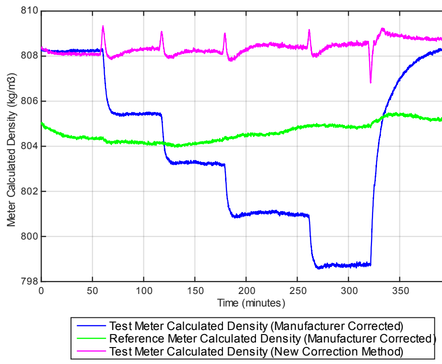


a)

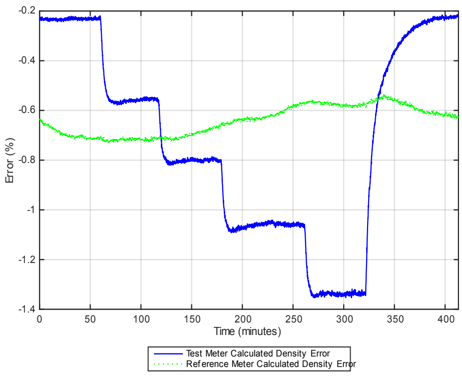
b) c)

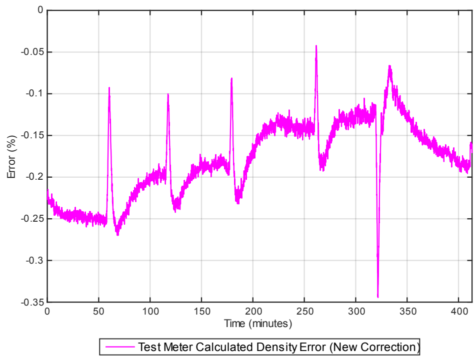
Fig. 5 – New Model vs Manufacturer Model - Density Calculation (Test Fluid – Water) a) Density Value Response, b) Manufacturer Method Errors c) New Method Errors

When the fluid was changed to kerosene and the test repeated, Fig. 6 shows that, accounting for a baseline offset of -0.2% error with respect to the known fluid properties, the manufacturer method contained a -1.2% error whereas the new method was shown to reduce this to a temporary ~+0.1% error during transition regions.



a)





b) c)

Fig. 6 – New Model vs Manufacturer Model - Density Calculation (Test Fluid – Kerosene). a) Density Value Response, b) Manufacturer Method Errors c) New Method Errors

4 New Method Transferability and Robustness

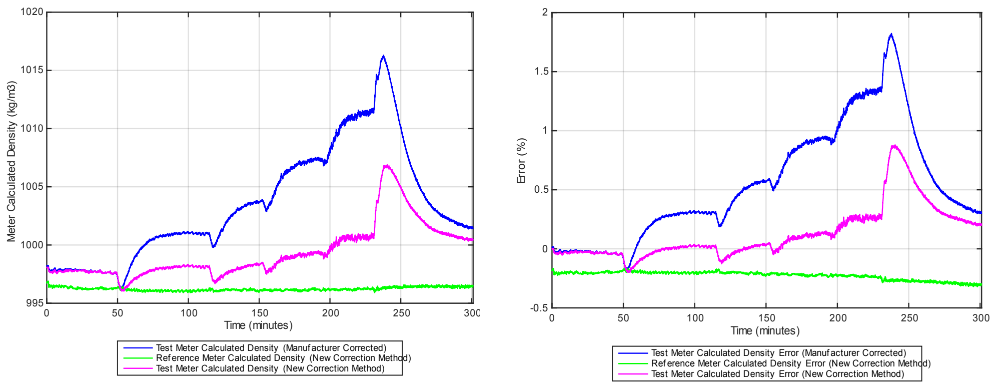
The test matrix detailed in Appendix 1 was used to assess the transferability of the new temperature compensation method to a new design of meter, which at the time of testing was still in the prototype stage. The testing was split into two stages:-

1. Direct comparison with the conditions described in section 3.
2. Expose the new method to extreme and non-uniform changes in ambient air temperature and fluid flow rate across three fluid properties (Water, Kerosene and Gas Oil).

This section summarises key test points that demonstrate the new method's improved response over the manufacturer's existing method.

4.1 Transferability Testing

Fig. 7 shows the calculated density values and associated errors with respect to the known fluid density using both the manufacturer's original method and the new correction method.

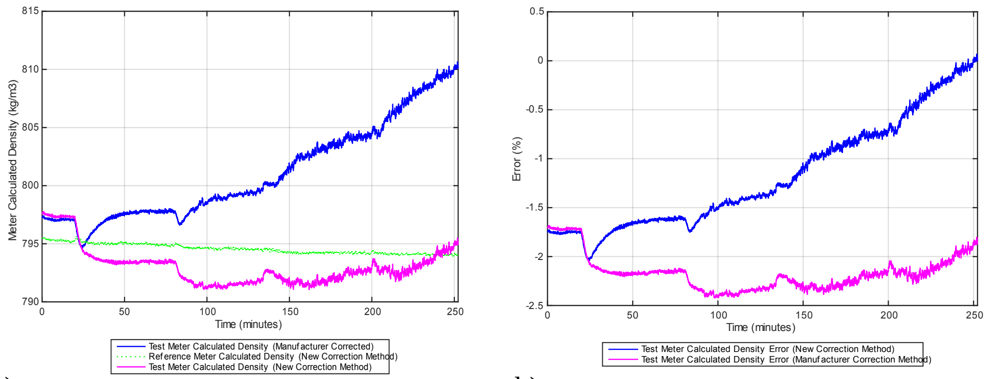


a) b)

Fig. 7 - Comparison of new correction method response vs original manufacturer correction method in water. a) Density response, b) Errors with respect to known fluid properties

The new correction method was observed to perform more efficiently than the manufacturer's method with an error of +0.25% present at the maximum ambient air temperature of 65°C. At the same air temperature, the manufacturer method reported a density value of 1012 kg/m3, which was in error of +1.3%.

Fig. 8 shows the calculated density values and associated errors with respect to the known fluid density of Kerosene using both the manufacturer’s original method and the new correction method.



a) b)

Fig. 8 - Comparison of new correction method response vs original manufacturer correction method in kerosene. a) Density response, b) Errors with respect to known fluid properties

The data revealed an offset in both the test and reference meters with respect to the true density at baseline conditions (20°C), with calculated density values containing a -1.7% error. This is a significant increase in meter baseline errors for kerosene when compared to the values observed in section 3, and further demonstrates the fluid dependency effect on temperature compensation effectiveness.

The negative offset combined with the increasing density value drift with respect to ambient air temperature shown is misleading as it would appear that the error for both manufacturer and new correction methods decrease during the course of the test. For clarity, Fig. 9 shows the tared data with respect to the baseline conditions established between 0 – 20 minutes.

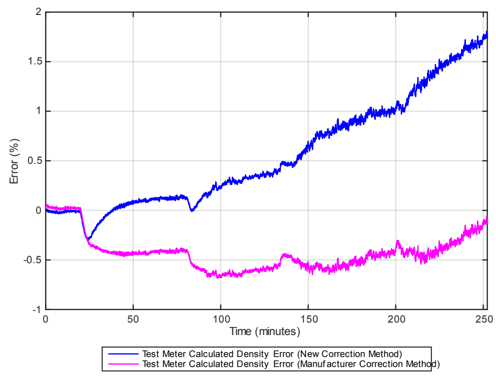


Fig. 9 - Resulting tared density calculation errors for kerosene with respect to baseline 20°C (air and fluid) conditions

Fig. 9 shows that by accounting for the initial offset, a maximum error value of -0.6% was observed using the new method compared to the maximum error of +1.75% in the manufacturer's correction algorithm.

4.2 Robustness Testing

Having established that the new temperature correction method is transferable to the prototype meter design, the data presented in this section pertains to non-ideal operating conditions.

4.2.1 Increasing Water Temperature with Sudden Test Meter Air Changes

The reference measurements for test 1 (Appendix 1) are shown in Fig. 10.

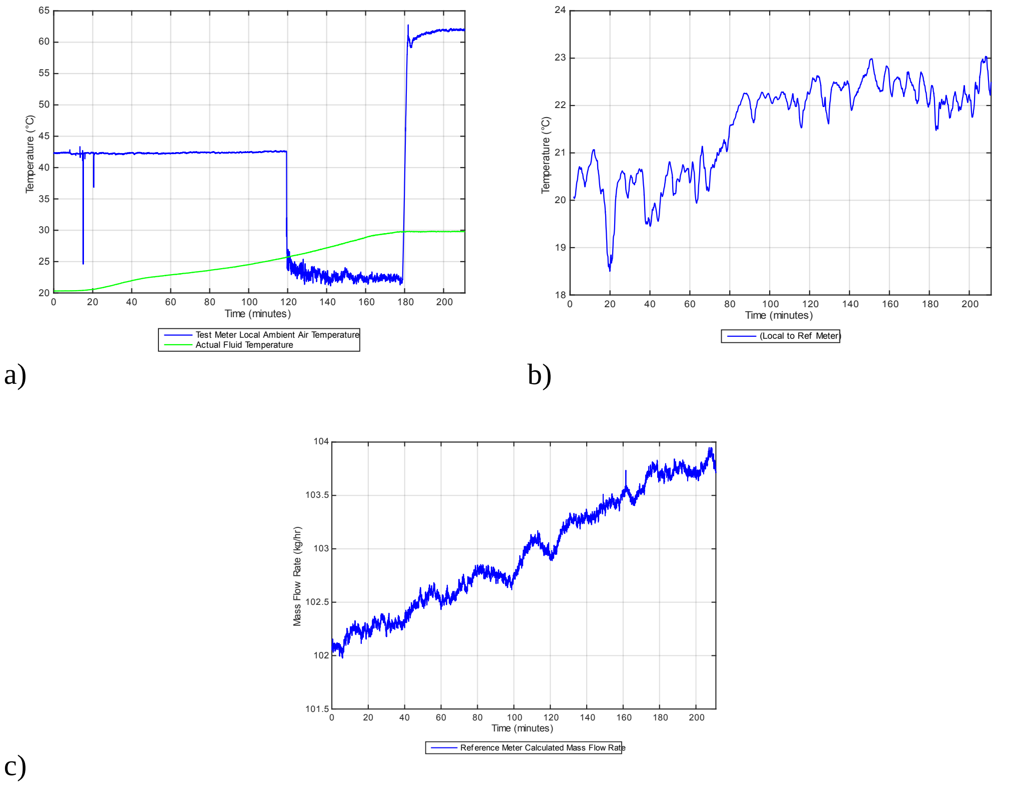
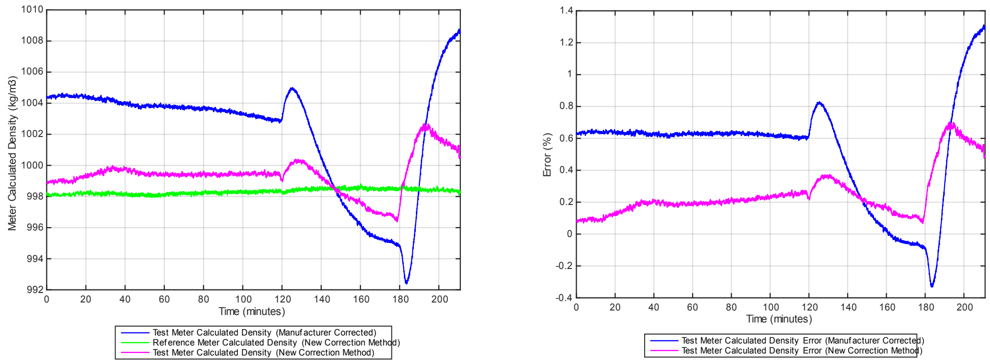


Fig. 10 - Reference measurements a) Test meter air temperature and actual fluid temperature, b) Reference meter air temperature, c) Mass flow rate

The performance of the new correction method with respect to the reference conditions is shown in Fig. 11.



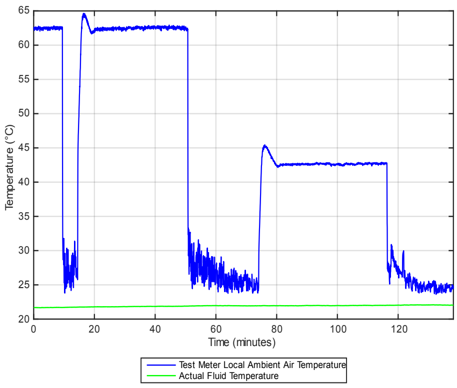
a) b)

Fig. 11 - Comparison of new correction method response vs original manufacturer correction method in water. a) Density response, b) Errors with respect to known fluid properties

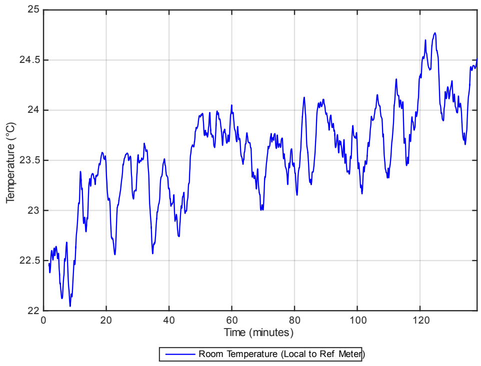
The data between 0 and 120 mins shows that the new method corrected for the already elevated ambient air temperature (42.5°C), with errors minimised to a maximum value of +0.25% compared to the +0.65% error observed from the manufacturers existing methods. When the test meter air temperature was rapidly cooled from 42.5°C to 22.5°C between 120 and 180 minutes, the error associated with new correction method is shown temporarily increase to +0.35% before falling to within the initial baseline value. When the air temperature is increased to 62°C at 180 mins, the error increases to a temporary value of +0.7% before beginning to show a decrease. In comparison, the manufacturers correction method error is shown to increase to +1.3% and shows no sign of reduction before the test ends at 210 minutes.

4.2.2 Kerosene - Sudden test meter air changes

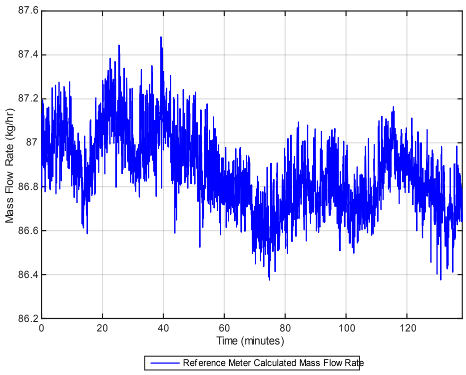
The data from Test 4 (Appendix 1) demonstrated the response of the new correction method in an environment where the surrounding air temperature is suddenly increasing and decreasing over a period of 2.5 hours. The reference measurements for test 4 are shown below in Fig. 12.



a)



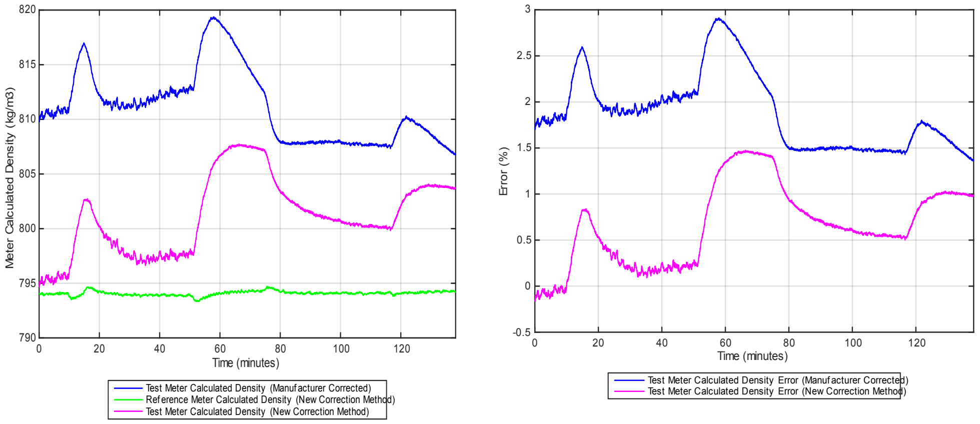
b)



c)

Fig. 12 - Reference measurements a) Test meter air temperature and actual fluid temperature, b) Reference meter air temperature, c) Mass flow rate

The response of the new correction method vs the manufacturer method is shown in Fig.13.



a) b)

Fig. 13. Comparison of new correction method response vs original manufacturer correction method in kerosene. a) Density response, b) Errors with respect to baseline 20°C (air and fluid) conditions.

The new correction method was found to contain temporary errors of +1.45% during the 60°C – 20°C cool down period (50 – 75 minutes). Note that the test started (0 - 10 minutes) with an elevated ambient air temperature of 60°C and as such the new correction method is shown to have corrected the density value to within an error -0.1% with respect to the baseline offset. During the same time period, the manufacturer method is shown to contain a 1.80% error.

4.2.3 Kerosene – Elevated test meter air temperature and sudden fluid flow changes

The data collected during test 8 (Appendix 1) shows the new correction method vs manufacturer correction method response to fluctuating flow rates at elevated ambient temperatures.

The reference conditions for the test are shown in Fig. 14. After an initial 20°C ambient steady state condition was achieved between 0 and 12 minutes, the test meter air temperature was increased to 60°C, where it remained for the duration of the test. The facility was then allowed to reach thermal equilibrium for 45 minutes, after which time the mass flow rate was reduced from 90 to 45 kg/hr (Fig. 14c). At 77 minutes the flow rate was then returned to 90 kg/hr where it remained until 105 minutes, at which point the flow was reduced to 0 kg/hr.

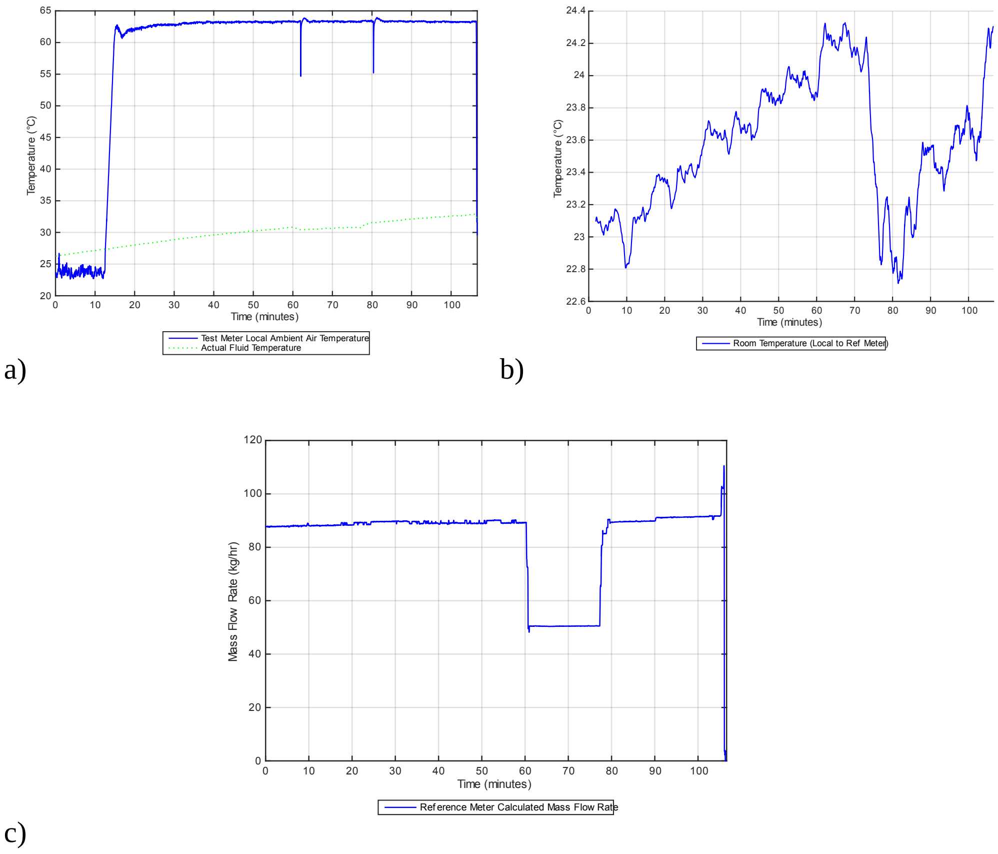


Fig. 14. Reference measurements a) Test meter air temperature and actual fluid temperature, b) Reference meter air temperature, c) Mass flow rate

The response of the new correction method vs the manufacturer method is shown in Fig. 15.

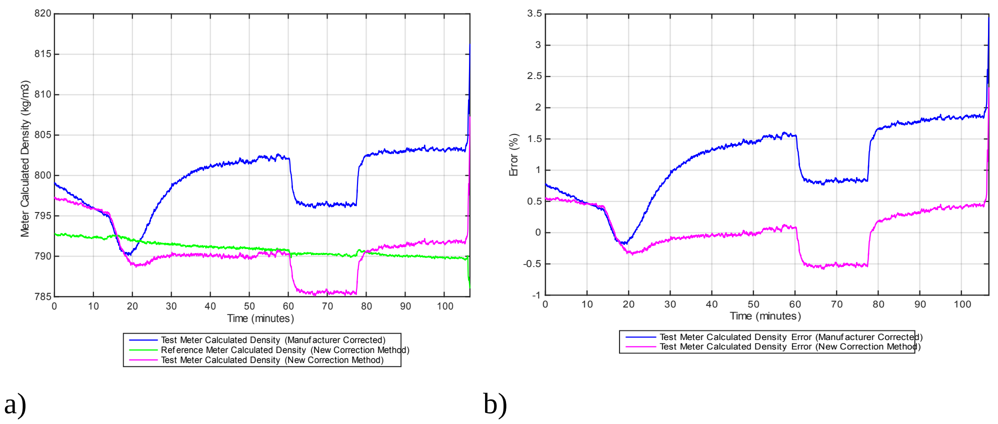


Fig. 15. Comparison of new correction method response vs original manufacturer correction method in gas oil. a) Density response, b) Errors with respect to baseline 20°C (air and fluid) conditions

The error on the new correction method output after the initial air temperature increase is shown to reach -0.25% (-0.75% reduction from starting point) and settle at 0% (a -0.5% reduction from starting point). The manufacturer's calculated density is shown to be +1.5% in error (an increase of 0.8% from baseline of this test). When the flow rate was reduced by 50% at 60 minutes, an immediate negative bias is imparted on both the manufacturer and new correction method data. The new correction method's density value was shown to contain a further -0.6% error, while the manufacturer's calculated value contained a further -0.7%.

5 Discussion and Conclusions

The tests and resulting data described herein have demonstrated that the new temperature compensation model is capable of calculating fluid density values containing reduced errors with respect to the known fluid properties when comparted to the existing methods used by the manufacturer. Specifically, this paper has highlighted that the new method was shown to be effective for water and kerosene over a number of fluctuating ambient and flowing conditions. The results have also demonstrated that the new correction method developed can be transferred to a different model of Coriolis meter produced by the project partner. The new method was shown to contain lower error values across the temperature differentials tested than the manufacturer's method.

The new correction method was also shown to contain lower error values than the manufacturer's method during extreme air temperature and mass flow fluctuations, as well as accounting for combinatory effects of increasing fluid temperatures.

The correction algorithm is only relevant to a specific manufacturer and the associated number and locations of temperature sensors on the meter body. However the underlying principle of deployment is relevant to any Coriolis meter designed in accordance with ISO 10790. With enough knowledge on manufacturer specific variances with respect to sensors, temperature compensation coefficients and initial factory setup conditions, the methods described could be adapted to suit multiple variants of the technology.

The solution was developed and validated in low flow conditions (1/4" meter size). The resolution of density measurement with respect to tube frequency is more challenging at this size. For example a change in frequency of 2Hz can represent the difference between the properties of air and water. The new method has been shown to be effective in these conditions, however a logical continuation of this work would be to undertake validation trials using larger meter sizes.

6 References

[1] T. Wang, R. Baker, Coriolis flowmeters: a review of developments over the past 20 years, and an assessment of the state of the art and likely future directions, Flow Meas. Instrum. 40 (2014) 99–123.

[2] M. Anklin, W. Drahm, A. Rieder, "Coriolis mass flowmeters: overview of the current state of the art and Latest research, " Flow Meas. Instrum. 17 (2006) 317–323.

[3] J. Ruoff, W. Gauchel, H. Kuck, Advances in Signal Acquisition and Signal Processing of Coriolis Flow Meters, in Eurosensors 2014, Procedia Engineering, 87, pp. 1585–1588.

[4] ISO 10790:2015, Measurement of Fluid Flow in Closed Conduits – Guidance to the Selection, Installation and Use of Coriolis Meters (Mass Flow, Density and Volume Flow Measurement).

[5] L. Wang, L. Hu, X. Fu, P. Ye, Experimental Investigation on Zero Drift Effect in Coriolis Mass Flowmeters, in FLOMEKO, Taipei, Taiwan, October 13–15, 2010.

[6] O. Øiestad, S. Fosse, S.Vervik, L. Falnes, Are Coriolis Mass meters suitable for Fiscal Liquid Applications? in North Sea Flow Measurement Workshop, Tønsberg, Norway, 2010

[7] M. P. Henry, D. W. Clarke, N. Archer, J. Bowles, M. J. Leahy, R. P. Liu, J. Vignos, F. B. Zhou, A self-validating digital Coriolis mass-flow meter: an overview, Control Engineering Practice, 8 (2000) 487-506.

[8] G. Lindsay, J. Hay, N. Glen, S. Shariatipour, Profiling and Trending of Coriolis Meter Secondary Process Value Drift Due to Ambient Temperature Fluctuations, Flow Meas. Instrum. 59 (2018) 225–232.

[9] G. Lindsay, N. Glen, S. Shariatipour, M.P. Henry, S. Churchill, Detecting and Correcting for Coriolis Meter Calculated Fluid Density Drift due to Ambient Temperature Variation in North Sea Flow Measurement Workshop, Aberdeen, 2018

[10] G. Lindsay, J. Hay, N. Glen, S. Shariatipour, Coriolis Meter Density Output – Detecting and Correcting Errors Induced by Ambient Air and Fluid Temperature Differentials, Flow Meas. Instrum. (Under final editorial review)

[11] M. Sadri, S. Shariatipour, A. Hunt, Effects of Flow Measurement Errors on Oil and Gas Production Forecasts, Computational & Experimental Methods in Multiphase & Complex Flow, 9 (2017) 115–133.

[12] C. Marshall, M. Sadri, H. Hamdi, S. Shariatipour, S.M. Lee, A.L. Thomas, J.S. Stewart, The Role of Flow Measurement in Hydrocarbon Recovery Forecasting in the UKCS, Journal of Porous Media, 22 (2019) 957-973

Appendix 1

Test No	Fluid	Highest Fluid Flow Rate (kg/hr)	Lowest Fluid Flow Rate (kg/hr)	Description of Fluid Flow Change (kg/hr)	Test Meter Air Temp Setpoint Pattern (˚C)	Time Spent at Test Meter Air Temp (hrs:mins)	Reference Meter Air Temp (˚C)	Initial Fluid Setpoint Temp (˚C)	Final Fluid Setpoint Temp (˚C)	Test Duration (Hrs)	Comment
1	Water	100	100	N/A	40, 20, 60	2:00, 1:00, 1:00	20	20	30	3.5	Fluctuating test air temperature, increasing fluid temperature
2	Water	100	100	N/A	20, 30, 40, 50, 60	1:00, 1:00, 1:00, 1:00, 1:00	20	20	20	5	Increase in test air temperature (repeat of standardised phase 2 tests)
3	Kerosene	86	86	N/A	20, 30, 40, 50, 60	1:00, 1:00, 1:00, 1:00, 1:00	20	20	20	5	Increase in test air temperature (repeat of standardised phase 2 tests)
4	Kerosene	86	86	N/A	60, 20, 60, 20, 40, 20	0:15, 0:05, 0:30, 0:30, 0:30	20	20	20	2.5	Fluctuating test air temperature
5	Kerosene	82	82	N/A	20, 30, 40, 50, 60	1:00, 1:00, 1:00, 1:00, 1:00	20	13	15	5	Viscosity effects test – chilled fluid, increase in test air temperature
6	Kerosene	82	82	N/A	60, 20, 60, 20, 40, 20	0:15, 0:05, 0:30, 0:30, 0:30	20	15	15	2.5	Viscosity effects test – chilled fluid, fluctuating test air temperature
7	Kerosene	86	86	N/A	20, 40, 25	0:30, 1:00, 0:20	20	20	30	2	Fluid heating over two stable test air temperatures
8	Kerosene	88	50	Reduced to 50 for 20 mins then returned to 88	60	2:30	20	20	20	1.5	High test air temperature, fluctuating flow
9	Gas Oil	45	45	N/A	20, 40, 20, 60	0:05, 1:00, 0:30, 0:30	20	20	30	2.5	Fluid heating with test air temperature fluctuation
10	Gas Oil	40	40	N/A	20, 30, 40, 50, 60	1:00, 1:00, 1:00, 1:00, 1:00	20	14	18	3.5	Viscosity effects test – chilled fluid, increase in air temperature
11	Gas Oil	40	40	N/A	60, 20, 60, 20, 40, 20	0:15, 0:05, 0:30, 0:30, 0:30	20	17	17	2.5	Viscosity effects test – chilled fluid, fluctuating test air temperature
12	Gas Oil	47	47	N/A	20, 30, 40, 50, 60	1:00, 1:00, 1:00, 1:00, 1:00	20	20	20	5	Increase in test air temperature (repeat of standardised phase 2 tests)
13	Gas Oil	47	47	N/A	60, 20, 60, 20, 40, 20	0:15, 0:05, 0:30, 0:30, 0:30	20	20	20	2.5	Fluctuating test air temperature

Test No	Fluid	Highest Fluid Flow Rate (kg/hr)	Lowest Fluid Flow Rate (kg/hr)	Description of Fluid Flow Change (kg/hr)	Test Meter Air Temp Setpoint Pattern (˚C)	Time Spent at Test Meter Air Temp (hrs:mins)	Reference Meter Air Temp (˚C)	Initial Fluid Setpoint Temp (˚C)	Final Fluid Setpoint Temp (˚C)	Test Duration (Hrs)	Comment
14	Gas Oil	45	25	10 / 10 mins (returned to 45 at end)	40	2:00	20	20	20	2	Fluctuating flow, extended logging at end to observe settling time
15	Gas Oil	45	25	10 / 10 mins (returned to 45 at end)	60	3:00	20	20	20	3	Fluctuating flow, extended logging at end to observe settling time (higher test air temperature)