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Detecting and Correcting for Coriolis Meter Calculated Fluid Density Drift due to Ambient Temperature Variation

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1 INTRODUCTION

Coriolis metering technology is now widely implemented throughout industry and is considered to be one of the most effective methods to monitor the mass flow rate of fluid within a pipeline. It is also well known that Coriolis meters have the ability to determine the density of the fluid present within its internals. There is now an increased interest from the Oil and Gas industry in utilising this density measurement capability as the primary process value to be output from the technology in applications such as precision control for fluid property conditioning as well as fluid contamination monitoring and control applications.

However, within the industrial environments in which these applications tend to be required it is common for there to be considerable fluctuation in the ambient conditions in which the meter is installed.

This paper details research data obtained using NEL's 'Very Low Flow' single phase facility. The rig has been modified to include a programmable temperature enclosure. The results clearly show significant drift in the calculated fluid density output by a Coriolis meter when it is subject to fluctuations in the surrounding ambient air. The fluid properties of the test medium were confirmed to be stable using NEL's UKAS standard reference instrumentation. Using the high-resolution data sets obtained from this research programme, a modified density correction model to better compensate for these ambient temperature effects has been developed and the improved performance from said model is demonstrated.

The rig and test matrix which form the basis of the results were developed over two distinct research phases with input from several meter manufacturers and end users.

The model demonstrates that correcting the reported fluid density for ambient variations is viable so that any system using the density value e.g. a PID control system, will not lose efficiency when the ambient air temperature varies. The resulting cost savings are therefore considerable.

Previous temperature corrections for Coriolis meters have focussed on the process fluid temperature and there is little published data on systematic investigations of ambient temperature. This work forms part of a 4-year doctoral research program investigating the influence of ambient conditions on Coriolis meter accuracy.

2 Background

The continual development of Coriolis flow metering technology has been well documented and summarised by [1], [2] and [3]. During the evolution of this technology, a device design has been largely conformed to. While manufacturer and application specific variations exist, the common design principle revolves around a single or dual flow tube, which is manufactured in either a straight or curved configuration. The flow tubes are mechanically driven to oscillate at their natural frequency. Displacement (or more usually 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 (Fig. 1). 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.

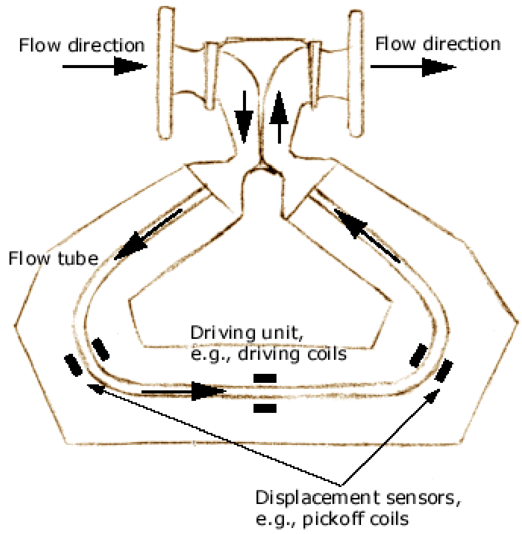

Fig. 1 – Coriolis Mass Flow Meter Component Overview

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 determined from the resonant frequency of the flow tubes and is defined in [4] as

$$f_{rf} = (1/2\pi).(C/m)^{1/2} \tag{1}$$

$$m = m_{tb} + m_f \tag{2}$$

$$m_f = (\rho_f).(V_f) \tag{3}$$

where

- f_{rf} is the resonant frequency
- C is the mechanical stiffness/spring constant

- m is the total mass
- m_{tb} is the mass of the oscillating tube(s)
- m_f is the mass of fluid within the oscillating tubes(s)
- V_f is the volume of fluid within the oscillating tubes(s)
- ρ_f is the density of the fluid

To calculate the density of the fluid present within the flow tube the following equation can be used by substituting in equations 1, 2 and 3 to produce equation 4.

$$\rho_f = \left\{\frac{C}{\left[V_f\left(2\pi f_{rf}\right)^2\right]}\right\} - m_{tb}/m_f \qquad (4)$$

The concept of ambient air temperature affecting the quality of the data output from Coriolis technology has been noted in previous experimental research programs. Research described in [5] on the subject of 'zero drift' highlighted ambient temperature variation as a contributing factor. In [6], where the suitability of Coriolis technology was assessed for a specific industrial application, it was again noted that ambient air fluctuations, which were intentionally introduced into the system by the research team, caused a detectable drift in the meter k-factor.

It should be noted that [5] and [6] do not address the effects of ambient air temperature on the fluid density output from Coriolis meters. It is this gap in knowledge that this research intends to address.

The diagnostic capabilities of Coriolis transmitters which are responsible for analog signal interpretation, digitisation and process value correction have been discussed previously at the South-East Asia conference [7]. Significant research has also been conducted with respect to developing the capabilities of the transmitter. In particular, research conducted by [8] focused on the creation of a self-validating sensor (SEVA), capable of fault detection and data correction to ensure measurement quality is upheld.

An initial research phase into the effects of controlled fluctuations in the air temperature surrounding a Coriolis flow meter with a continuous flowing fluid with known physical properties was carried out at NEL and published in [9].

The effects demonstrated in [9] were presented to a Coriolis manufacturer and a partnership was formed, the key research objective being to develop an intelligent temperature correction model that significantly reduces the errors demonstrated in [9] and which can be readily implemented in a transmitter. 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 presented in this paper are a continuation of the research from [9] and a direct result of the manufacturer partnership.

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 [10] and [11].

3 Test Design

To ensure that fine control over all potential variables was achieved, NEL's 'Very Low Flow Facility' was used. The reduced pipe bore, measuring at 8mm (inner diameter) throughout the facility, ensured fine temperature control on a minimised mass of fluid, compared to NEL's larger flow facilities. The facility itself is housed in a laboratory that is of dimensions 4m x 3m x 2m, which reduces the potential for significant uncontrolled ambient temperature fluctuation. The detail of both the facility build and test matrix are described in sections 3.1 and 3.2.

3.1 Facility Layout and Equipment

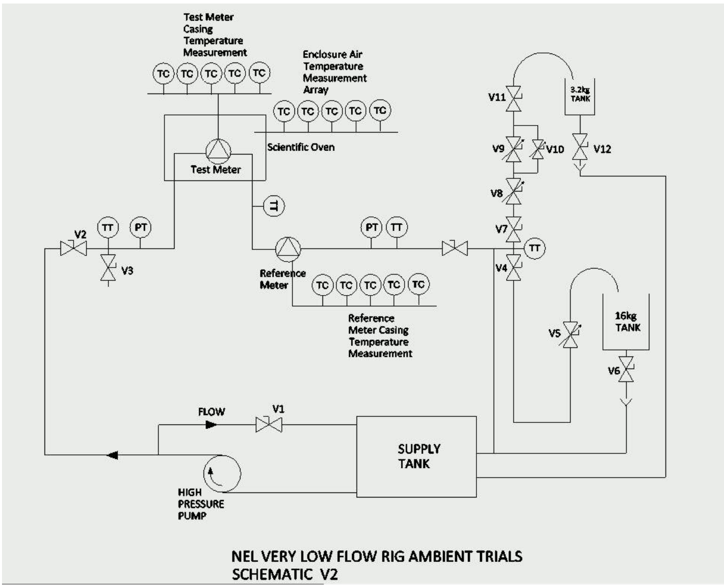

Fig. 2 – Facility setup and Instrumentation Overview

NEL's 'Very Low Flow Facility' (Fig. 2) was modified to allow the piping of the test section to enter and exit an environmental chamber. Within this environmental chamber a ¼" Coriolis mass flow meter (the 'test' meter) was installed and connected to the incoming and outgoing test section pipes. Downstream of the test meter/temperature enclosure an identical Coriolis meter (the 'reference' meter) was installed in series, but at ambient temperature. To ensure that fluid properties were not altered due to heat exchange from the circulation pump, the temperature enclosure or the test meter body at an elevated temperature, reference PRTs were installed in key locations throughout the loop. Fluid temperature variations can thus be monitored and their overall impact on the test objective assessed. The facility was run in recirculation mode. A gravimetric calibration of both meters was also conducted to confirm meter performance and calibration information. This facility configuration is identical to that described in [9], using a different reference and test meter shape, size and manufacturer.

In order to fully understand the effects of ambient temperature fluctuation on the metering technology, 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. This was a key requirement for this phase in the research program as it allowed for a detailed understanding as to how the meter physically reacts to the test conditions as well as allowing for an assessment of the efficiency of the existing temperature correction algorithms.

Using the integrated Modbus registers specific to the devices under test, the data acquisition system was able to log key process values by polling a Modbus server to which both the reference and test meter were uploading data every 1 second.

The manufacturer's correction algorithms were deactivated on both the reference and test meter 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 relevant correction algorithms were applied to each individual instrument scan as opposed to the overall average value to ensure that a direct comparison of both raw and corrected value could be undertaken.

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

3.2 Testing Conditions

To effectively target the underlying cause of error in meter calculated fluid density the following test parameters were controlled and monitored throughout the research program:

- Fluid Temperature
- Room Temperature
- Upstream Pressure
- Downstream Pressure
- Fluid Flow Rate (ensuring consistent residency time within environmental chamber's elevated temperature conditions)

While fluid flow rate was shown to affect the extent of meter density error during [9], the commissioning trials performed on the Coriolis meters used for this test programme highlighted that the fluid density process value (both uncorrected and corrected) is not sensitive to significant flow rate change at elevated ambient temperatures. Therefore, mass flow rates were kept constant throughout the tests, specifically at a rate which minimised fluid residency time in the temperature enclosure while ensuring the rig performed at optimum capacity in recirculation mode.

The following parameters were systematically varied to quantify the extent of their individual contributions to density error.

- Environmental chamber air temperature
- Fluid Properties

The results reported upon in section 4 are a direct result from the test matrix below in Table 1.

Table 1 – Ambient Air Temperature Variation Test Parameters

Test No	Fluid	Flow Rate (kg/hr)	Initial Test Meter Air Temp (°C)	Final Test Meter Air Temp (°C)	Rate of Enclosure Air Temp Change (°C)	Initial Reference Meter Air Temp (°C)	Final Test Meter Air Temp (°C)	Fluid Temp Setpoint (°C)	Test Duration (hrs)
1	Water	230	20	60	10 /1hr	20	20	20	7
2	Kerosene	230	20	60	10 /1hr	20	20	20	7

Before data collection was undertaken, the fluid was circulated through the facility for a period of one hour to ensure steady state conditions achieved. During this time the chamber door was open to ensure both the reference and test meter were exposed to the same ambient air temperature. Once steady state conditions had been confirmed, the data acquisition system was started. For the initial 20°C air temperature the chamber door remained open to ensure a true baseline air temperature was logged for both the reference and test meter. At the end of both tests 1 and 2 the chamber door was opened, and the fluid allowed to continue to circulate. This was done to observe the effect of 'rapid' cooling in the surrounding air temperature of a Coriolis meter and its process values (raw and corrected).

4 Results

The focus of this paper is the fluid density values generated by the meter, and the results reported here reflect this limited focus. The performance of other process variables (e.g. mass flow) will be made available in future journal publications and the doctoral thesis arising from this research programme.

4.1 Key Reference Measurements During Testing and Data Analysis

Fig. 3. and Fig. 4. show the stepped increase of the enclosure air temperature for tests 1 and 2 respectively. The actual fluid temperature is also trended. The fluid temperature is shown to remain stable during the periods of sudden air temperature increase. During testing the fluid temperature increased by 1°C and 0.8°C for water and kerosene respectively. Therefore, when analysing the fluid density error reported by the test meter in the forthcoming sections it can be assumed that the fluid properties themselves are not varying beyond the expected effect of the recorded temperature values.

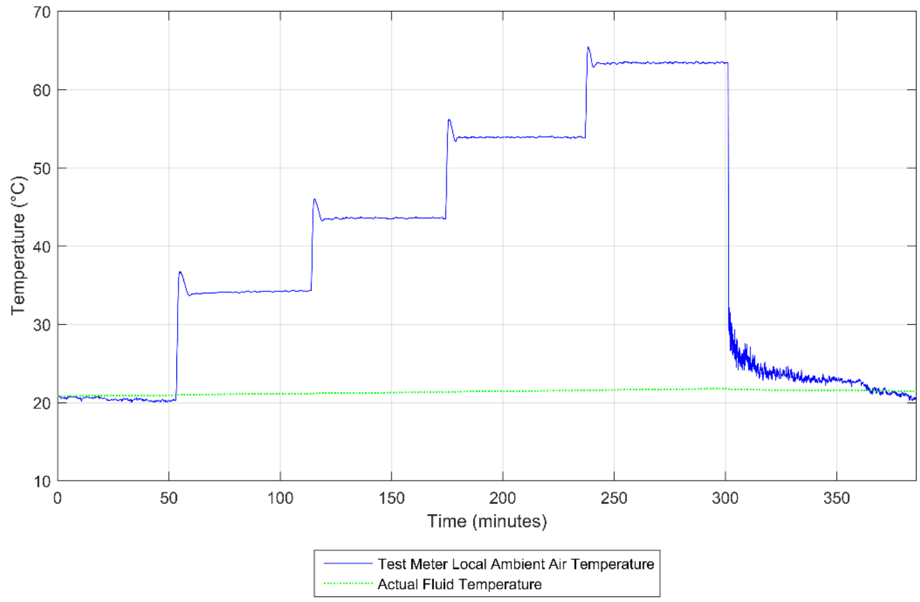

Fig. 3 – Test Chamber Temperature (Local Test Meter Air Temperature) & Measured Reference Fluid Temperature (Water)

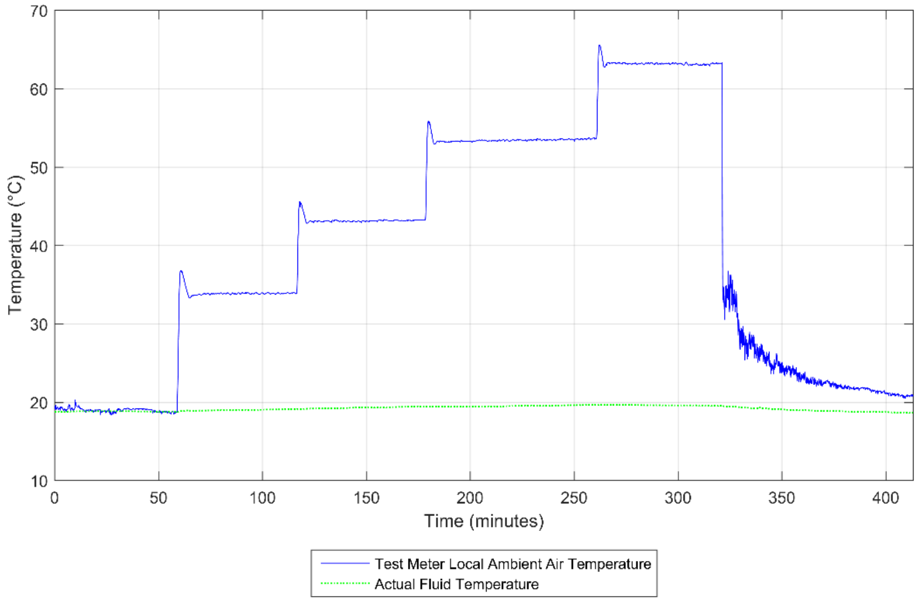

Fig. 4 – Test Chamber Temperature (Local Test Meter Air Temperature) & Measured Reference Fluid Temperature (Kerosene)

Fig. 5. and Fig. 6. show the corresponding room temperatures. The intention was to maintain the room temperature to within +-1°C of its initial value. However, unseasonably warm weather caused variations of +1°C/-4°C for the water trial and +4.1°C/-1°C for Kerosene. In practice, these wider ranges provided useful additional data for validating the correction technique.

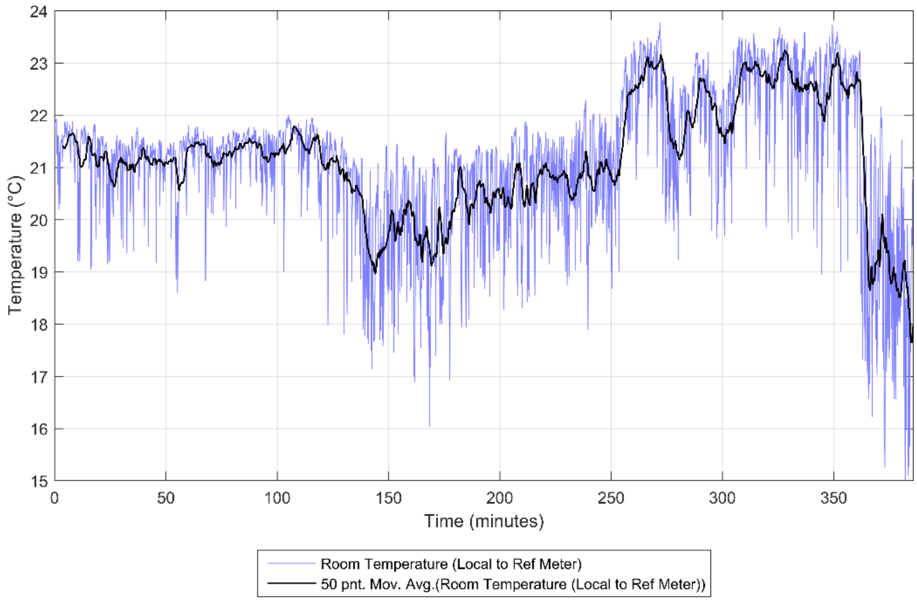

Fig. 5 – Room Temperature (Reference Meter Local Air Temperature) during Test 1

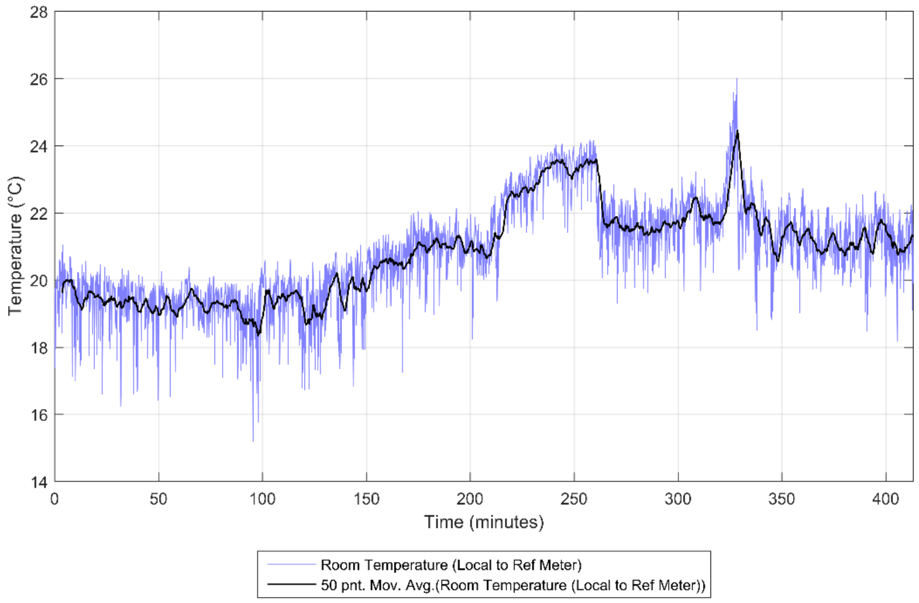

Fig. 6 – Room Temperature (Reference Meter Local Air Temperature) during Test 2

Fig. 7. and Fig. 8. detail the properties of water and kerosene between 5°C to 55°C. The calibration data was generated from direct fluid samples and analysis in NEL's fluid property laboratory. This data was used for the determination of test meter true error.

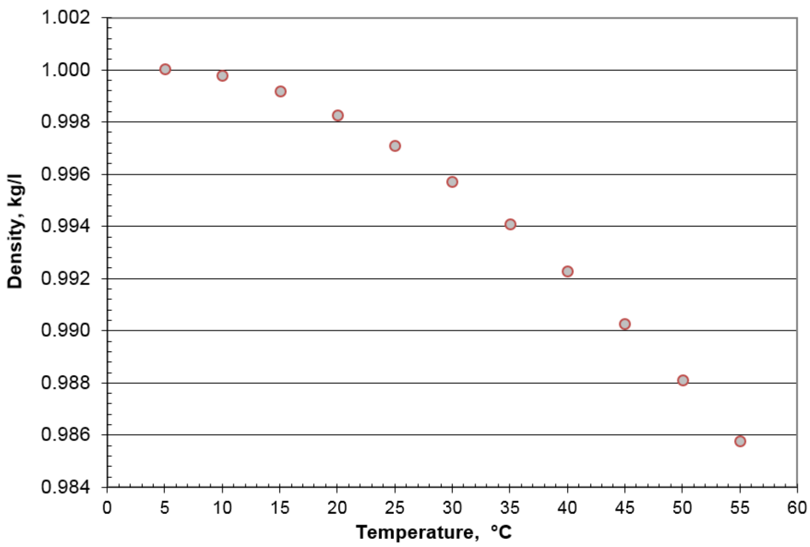

Fig. 7 – Test 1 Fluid (Water) Density Curve as determined by NEL's fluid property lab

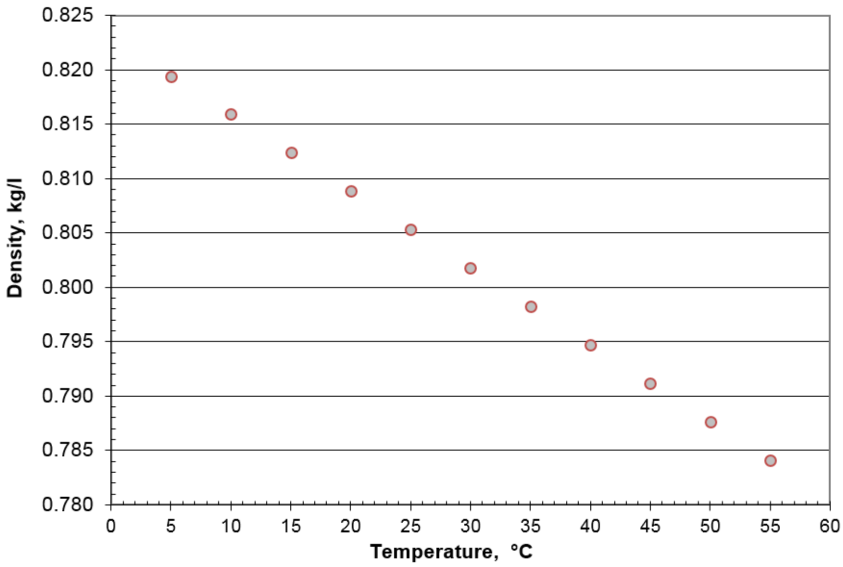

Fig. 8 – Test 2 Fluid (Kerosene) Density Curve as determined by NEL's fluid property lab

4.2 Meter Uncorrected Fluid Density Drift

The uncorrected values for reference and test meter densities are shown in Fig. 9. And Fig. 11.

Fig. 9. shows that for test 1, the test meter uncorrected density varied from 992 kg/m3 to 1075 kg/m3 due to ambient air heating (Fig. 3.) and therefore produced increasing errors up to 7.8% as shown in Fig. 10. The reference meter uncorrected fluid density followed the variations in room air temperature (Fig. 5.).

It should be noted that the baseline density value reported by the reference meter contained a -1.1% error, with the test meter baseline density containing a -0.6% error (compare Fig. 7.).

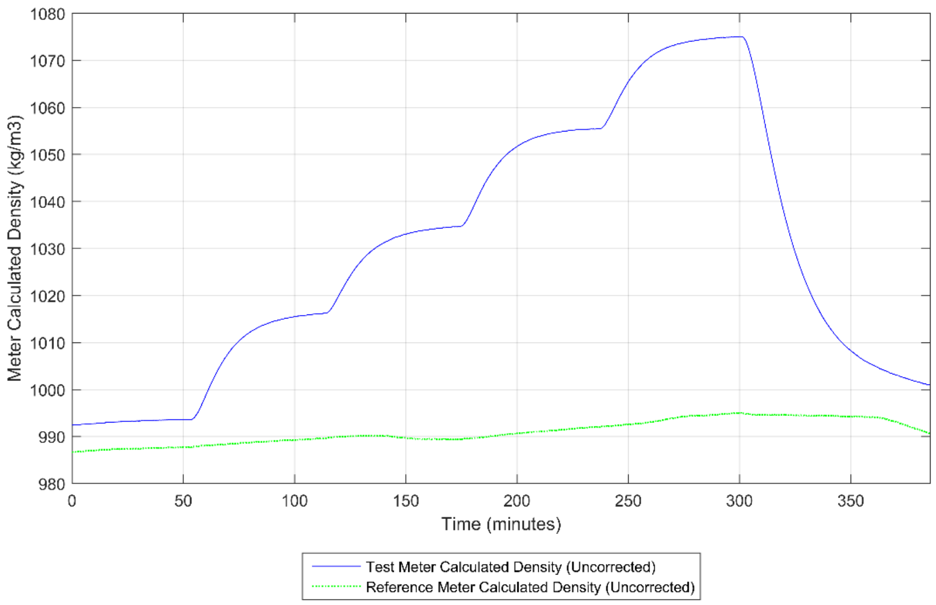

Fig. 9 – Uncorrected Test Meter Density Response Due to Local Ambient Temperature Change (Test Fluid – Water)

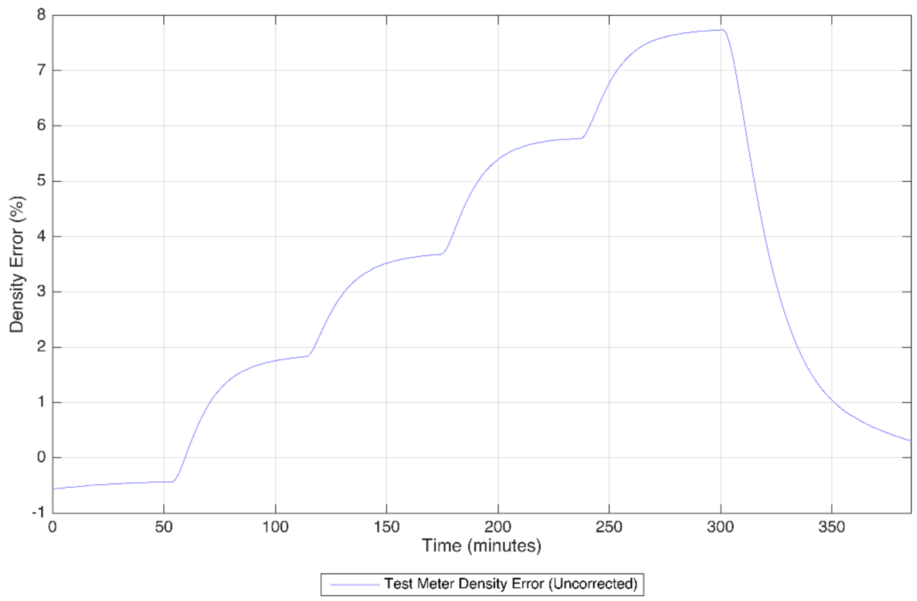

Fig. 10 – Uncorrected Test Meter Density Error from Reference Fluid Properties (Test Fluid – Water)

Similar patterns were observed in test 2. Fig. 11. shows a strong correlation between the ambient air temperature (Fig. 4.) and the uncorrected density value.

A change in uncorrected density from 786 kg/m3 to 871 kg/m3 was observed during the incremental heating stage of testing resulting in an error of 7.8% at 60°C ambient (Fig. 12.)

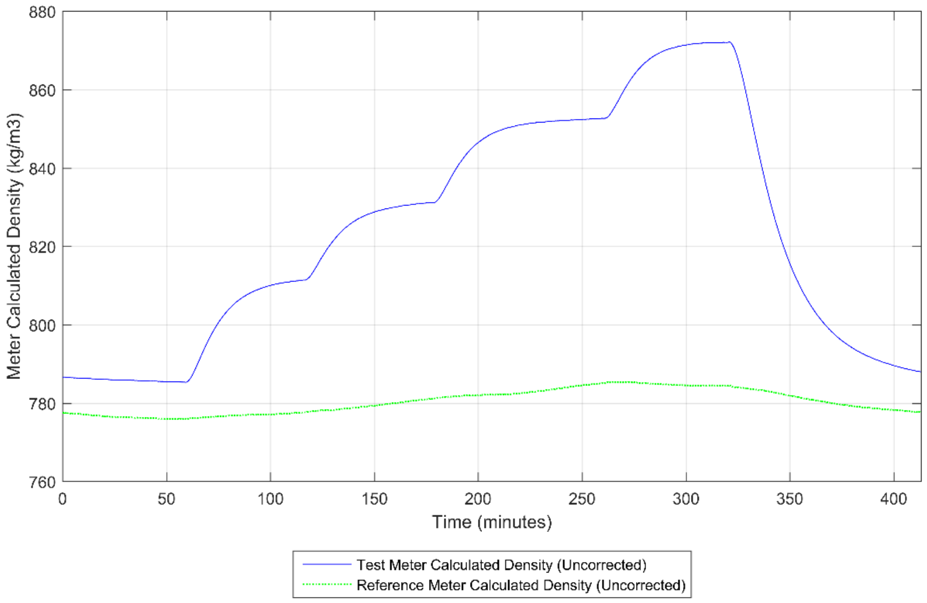

Fig. 11 – Uncorrected Test Meter Density Response Due to Local Ambient Temperature Change (Test Fluid –Kerosene)

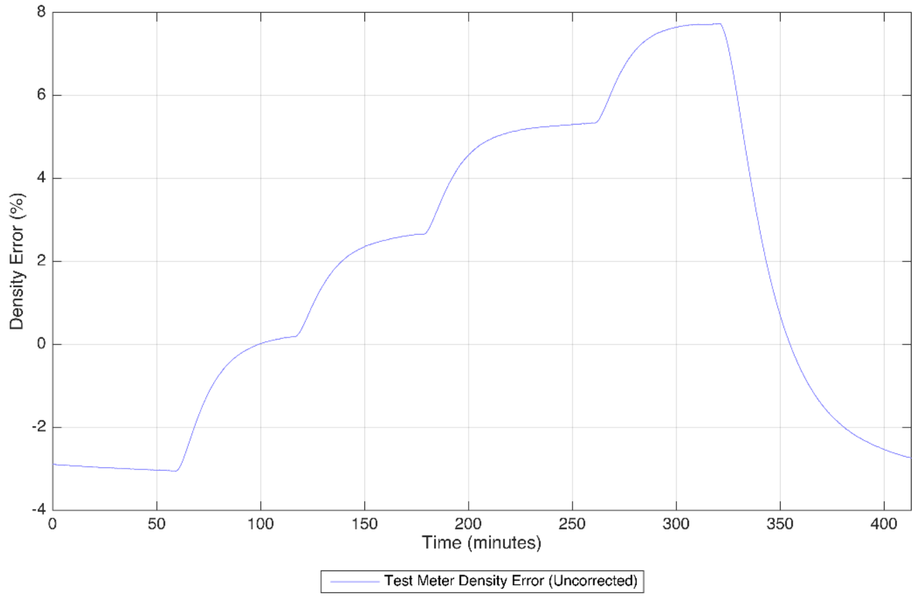

Fig. 12 –Uncorrected Test Meter Density Error from Reference Fluid Properties (Test Fluid – Kerosene)

The magnitude of the errors described above are however to be expected for raw uncorrected data.

4.3 Corrected Raw Values using existing Manufacturer Techniques

Fig. 13. and Fig. 14. show that when the manufacturers temperature correction algorithm is applied to the uncorrected data, the error is reduced. However, there is still a clear pattern that correlates with the air temperature changes. An error of -0.42% is still present on the test meter at the maximum ambient temperature. The reference meter corrected fluid density is shown to correlate to room ambient conditions (Fig. 5)
It should be noted that an offset of 0.08% is present for the reference meter when compared to both the test meter baseline value and fluid properties curve (Fig. 7.).

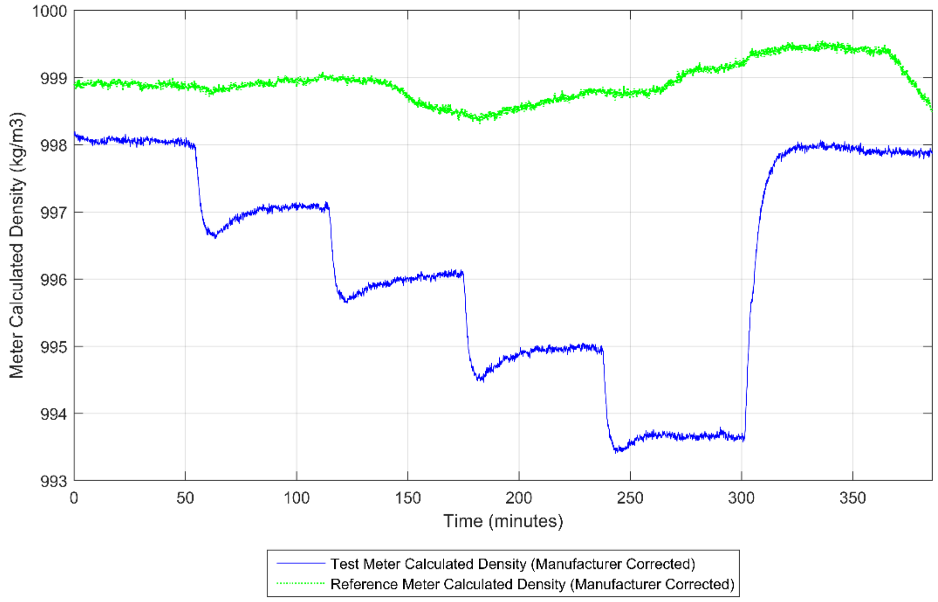

Fig. 13 – Corrected Test Meter Density Response Using Manufacturer Correction Methods
(Test Fluid – Water)

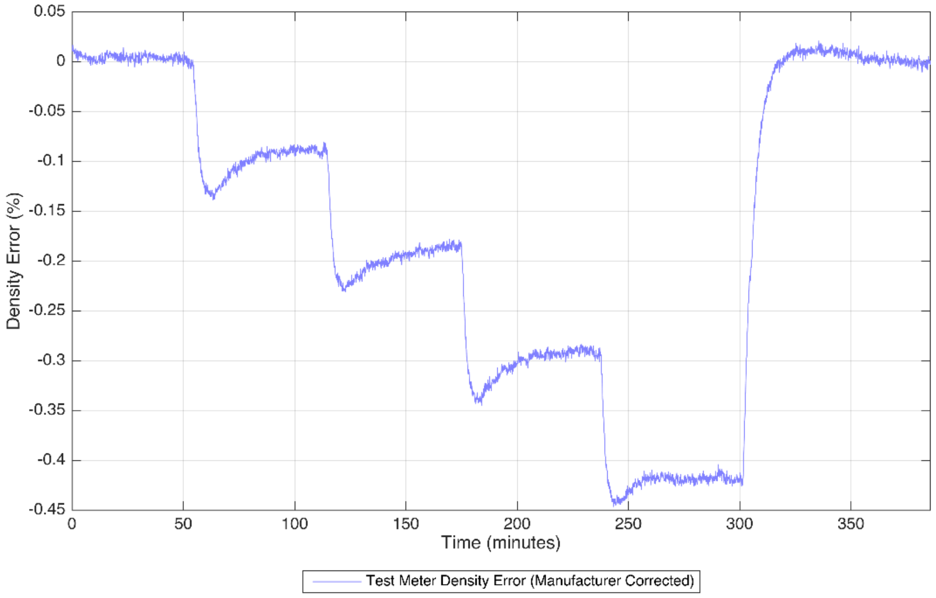

Fig. 14 – Manufacturer Corrected Test Meter Density Error from Reference Fluid Properties
(Test Fluid – Water)

As expected the corrected data for test 2 shown in Fig. 15. And Fig. 16. show similar trends to test 1. Here the test meter error reached a value of -1.3% at the maximum ambient temperature tested.

The initial baseline value for the test meter was shown to contain a -0.2% error from the know fluid property value (compare Fig 4 and 8). It should also be noted that the baseline error between the reference and test meter also increased to a value of -0.4% with the reference meter showing -0.6% error from known fluid properties.

The overall increase in errors highlights that the fluid density calculation and temperature compensation techniques currently implemented by the manufacturer are sensitive to fluid property changes.

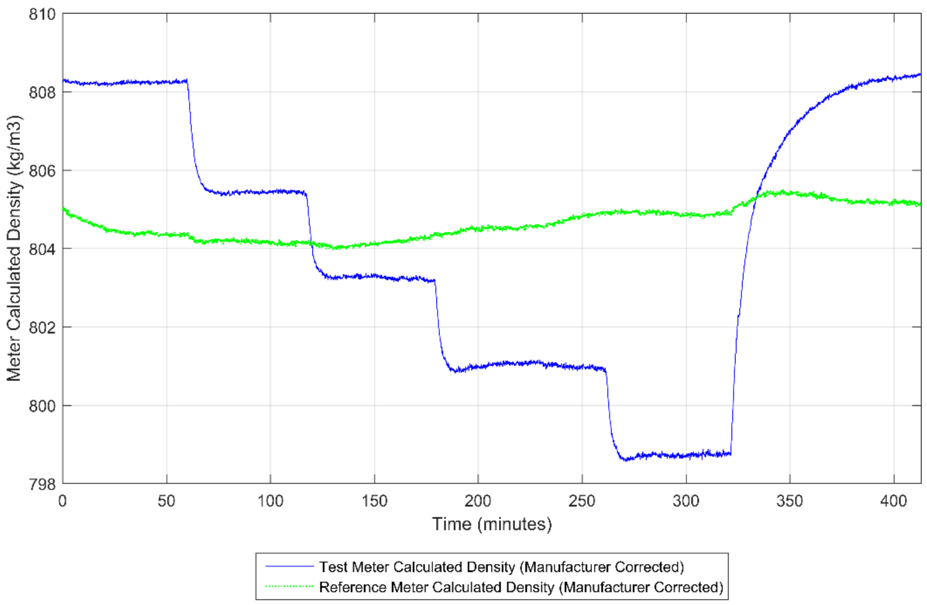

Fig. 15 – Corrected Test Meter Density Response Using Manufacturer Correction Methods
(Test Fluid – Kerosene)

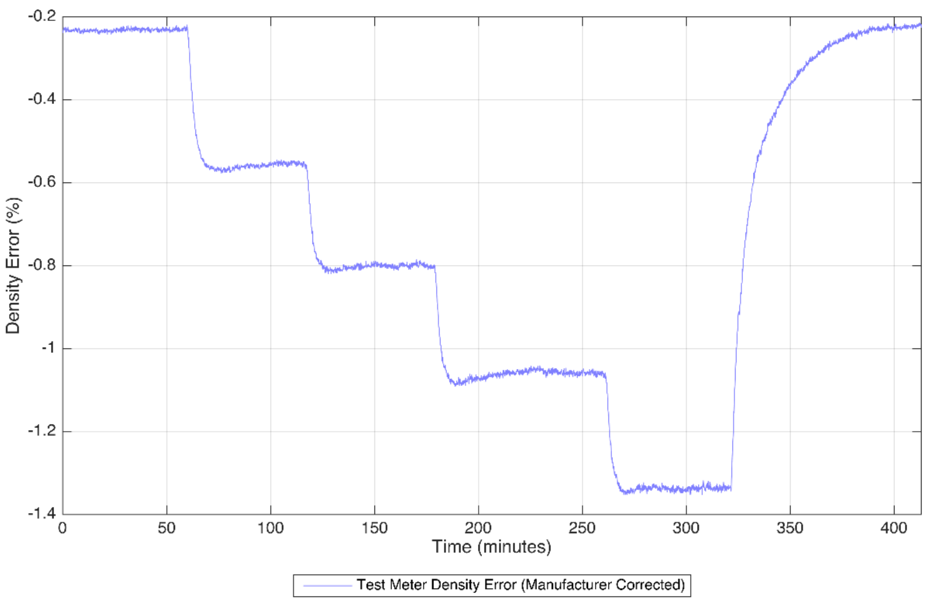

Fig. 16 – Manufacturer Corrected Test Meter Density Error from Reference Fluid Properties
(Test Fluid – Kerosene)

The data presented in this section highlights need for a new correction model, which can perform in fluctuating ambient conditions to ensure that end users can correctly measure the fluid properties present within the meter internals regardless of any changes in local air temperature in a given real world installation.

5. Modified Density Correction Model

Analysis of the 40+ process variables logged from both the reference and test meter via Modbus allowed for a comprehensive understanding of individual meter component response with respect to the temperature profiles experienced throughout the test programme. From this analysis, a modified density correction model has been developed.

Due to the confidential nature of the research, which at the time of writing is still an active project, the detail behind the correction model at this stage cannot be presented. However, the data presented in Fig. 17. – Fig. 20. clearly show a proof of concept as to how the model would perform if implemented in the meters under investigation.

The additional "New Correction Method" trendlines that have been added to the data from section 4.3 highlight that with respect to the test meter, for each 10°C increment in the surrounding ambient air temperature, the modified correction method correctly detects the increasing error in meter output due to the excessive temperature differentials. As such, the algorithm applies the appropriate correction. The post processed data shows that the density value consistently returns to the 'correct' fluid density value once steady state conditions have been achieved.

Fig. 17. And Fig. 18. show that for test 1, the test meter density error is now limited to a temporary value of -0.12% before recovering to the expected value (Fig. 7.). The reference meter data remains unchanged. This is due to the fact that, in its present form, the new correction method has not been tuned to account for the lesser temperature effects that the reference meter was subjected to during testing. Therefore, the new correction method does not alter the data produced for the reference meter.

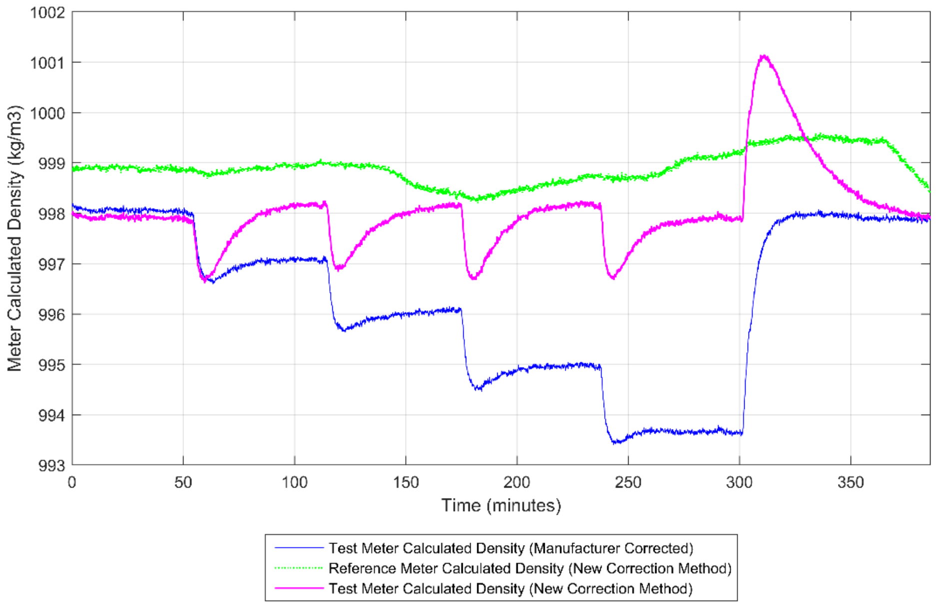

Fig. 17 –Corrected Test Meter Density Response Using New Correction Model
(Test Fluid – Water)

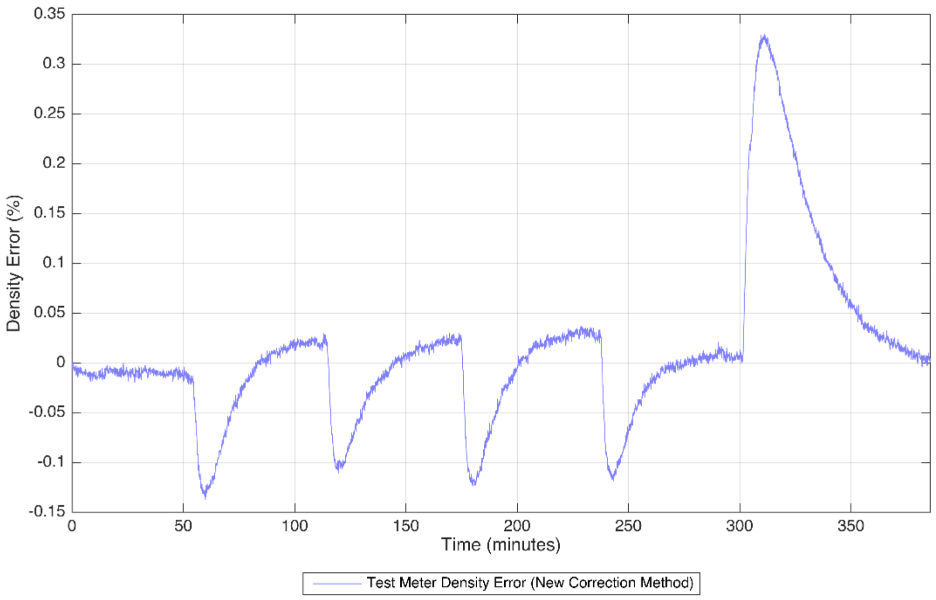

Fig. 18 – New Correction Method Test Meter Density Error from Reference Fluid Properties
(Test Fluid – Water)

When the new model is applied to the test 2 data, Fig. 19. shows that the model correctly detects that error in the meter output is present resulting in intervention and correction to the expected value (Fig. 8.). Fig. 20 shows that the temporary error in 'New Correction Method' value is now shown to be ~-0.25% (considering initial -0.2% offset from true density value) during each ambient temperature step change before eventual recovery to the expected value. Again the reference meter data is not altered by the model.

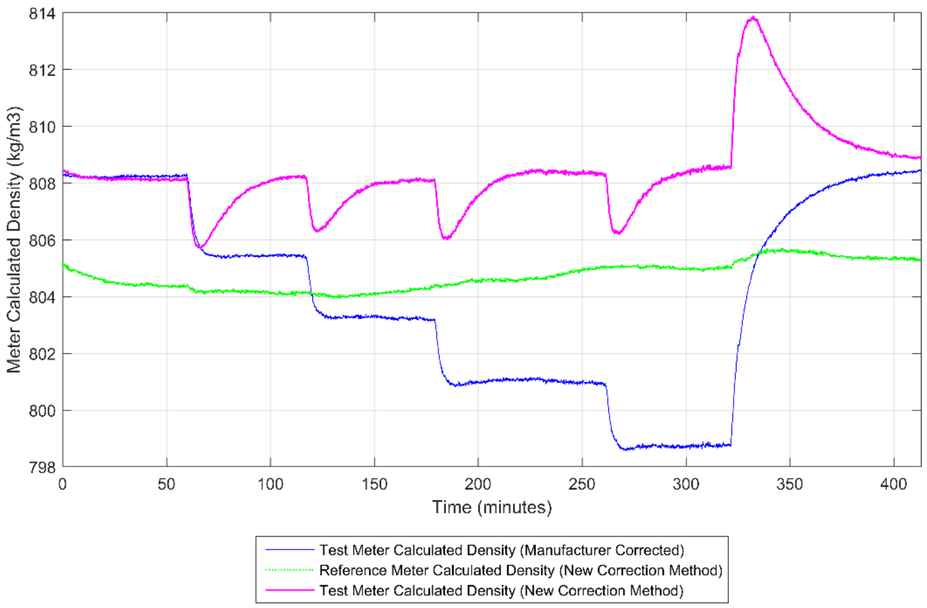

Fig. 19 – Corrected Test Meter Density Response Using New Correction Model (Test Fluid – Kerosene)

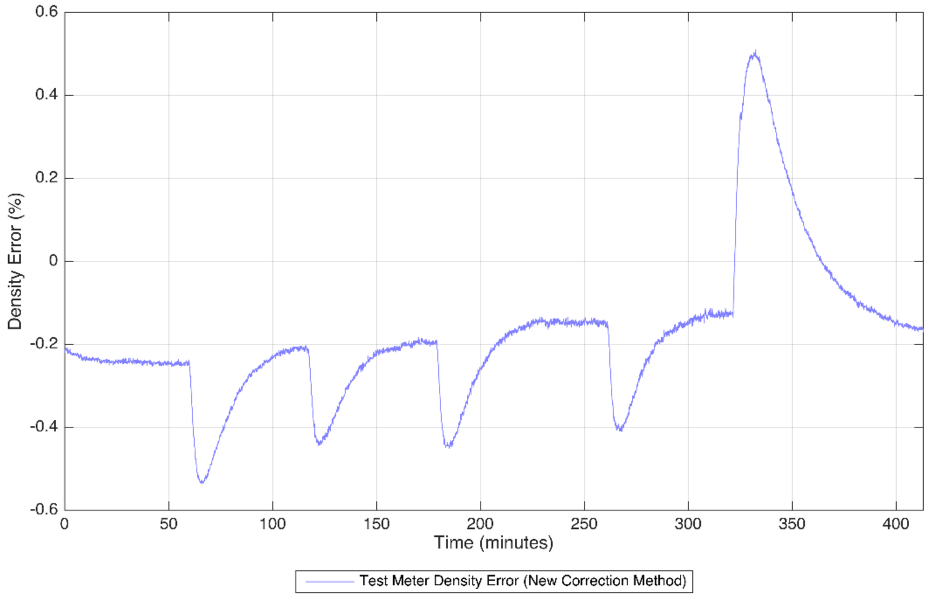

Fig. 20 – New Correction Method Test Meter Density Error from Reference Fluid Properties
(Test Fluid – Kerosene)

6. Discussion and Conclusions

The density correction model demonstrated has provided a proof of concept for live compensation of the effects from ambient air temperature fluctuation on Coriolis meter density calculation. The model has been shown to provide the correct value for fluid density across a range of elevated ambient temperature conditions as well for fluids of differing physical properties.

While a temporary error can still be observed in the new correction method output, this only occurs during the period of thermal stabilisation. During this period the drift for water has been reduced from a maximum possible value of -0.42% to -0.12% (at 60°C ambient). For kerosene, the drift has been reduced from maximum possible value of -1.3% to -0.25% (at 60°C ambient). Once thermal equilibrium has been achieved the new correction model is able to produce the correct density value.

The model in its current form has been developed using process values and sensors already present on the meters. Going forward into the final phase of the research project there will be an additional focus on further developing the model demonstrated by modifying the existing meter design by way of additional sensors. The correction algorithm will be modified to account for the additional sensor inputs and the performance of the algorithm analysed throughout the trials. The test matrix will also be modified to account for subtle fluctuations in ambient conditions as well as creating imperfect flow and temperature control conditions. This will allow for a realistic assessment of the correction model performance.

The model was not able to further compensate for the baseline errors observed. Further consultation with the manufacturer as well as further development of the model shall take place in the next phase of research to further optimise the algorithm coefficients including the manner in which they are generated to ensure the new correction model can function as efficiently as possible.

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