New Generation Vibrating Tube Sensor for Density Measurement under Process Conditions

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1. Introduction

Density is one of the most prominent means to classify the physical properties of crude oil and refined products and as such, accurate density measurement has significant importance and value to the hydrocarbon processing industry. Continuous density measurement is used in the determination of quantities for custody transfer and allocation measurements, inventory control, product quality control, blending applications as well as interface detection. The most stringent density performance requirements for accuracy, repeatability, linearity and reproducibility are normally found in custody transfer applications and those applications impacting financial reporting or taxation. Custody transfer systems require both a density and a volume or mass component of sufficient accuracy to determine fiscal quantities. Furthermore, determination of quantities by inferred mass, where metering is done on a volumetric basis but reporting is in mass terms, require the lowest density uncertainties due to the direct first order effect of the density measurement uncertainty to the overall uncertainty of the reported quantity. Volume based determinations also require a density component such that the volumetric quantity can be calculated at reference conditions of pressure and temperature, however, the effect of the density uncertainty on the total uncertainty is less pronounced.

In recent years the errors associated with continuous in-field density measurement have received special attention from the industry. The main concern revolves around the performance of density meters operating at process conditions that differ from laboratory calibration conditions. In addition to accurate measurement over a wide range of fluid densities, users also require precise measurement at elevated process pressure and temperature as well as across varying fluid viscosities and changing ambient temperatures.

Devices that utilize a vibrating element to determine the natural resonance frequency of the process fluid in order to determine fluid density are commonly found in the crude and refined product applications described above. Coriolis mass flowmeters used in industry for highly accurate flow measurement also are able to determine process fluid density by similar means. For a newly introduced Coriolis mass flowmeter, a detailed overview of sensitivities and accuracies for density measurement will follow a brief introduction to the meter properties and working principle.

2. Meter design and function

In Figure 1 the design of Endress+Hauser Proline Promass Q 300 is shown. The light weight, compact and drainable Coriolis mass flow meter is offered with all industry standard process connections in four different line sizes from 1 to 4 inch. Process temperature and pressure ranges are -196…205 °C and 0…100 bar respectively. Transmitters with a variety of standard outputs and communication protocols are available.

The internal structure is depicted in Figure 2. Two parallel and bent measuring tubes are connected via flow splitters to the process line. Coupling elements at the inlet and outlet of the meter define the oscillation length of the working mode. Equivalent to a tuning fork, both tubes vibrate in opposite directions so the system is balanced and energy is conserved in the oscillator, shown in Figure 3. Via an electrodynamic driver at the tube center and two electrodynamic sensors at the tube inlet and outlet the transmitter control algorithm generates a harmonic tube vibration at resonance frequency and constant amplitude, thereby compensating tube damping forces.

The working principle of Coriolis mass flow meters has been described in many publications, e.g. [1]. Tube resonance frequency f_r depends on tube stiffness, tube mass and fluid mass load as a function of fluid density ρ. Fluid density ρ is influenced by a number of parameters and can be derived from measured raw resonance frequency f_r by

$$f = f_r(p, v, \gamma) \qquad (1)$$

$$\rho_r = C_0(T_m) + C_1(T_m, T_h)\, f^{-2} \qquad (2)$$

$$\rho = \rho_r(\eta, c) \qquad (3)$$

where f, p, v and γ are compensated frequency, process pressure, flow velocity and orientation angle. ρ_r, T_m, T_h, C_0 and C_1 are raw density, mean measuring tube temperature, housing temperature and calibration constants. Finally η and c are fluid viscosity and fluid speed of sound respectively. All the parameters which influence density are compensated based on internal signals, except of the pressure effect which can be corrected by a manually entered value or by reading in an external pressure transducer.

Figure 1: Design of Endress+Hauser Proline Promass Q 300.

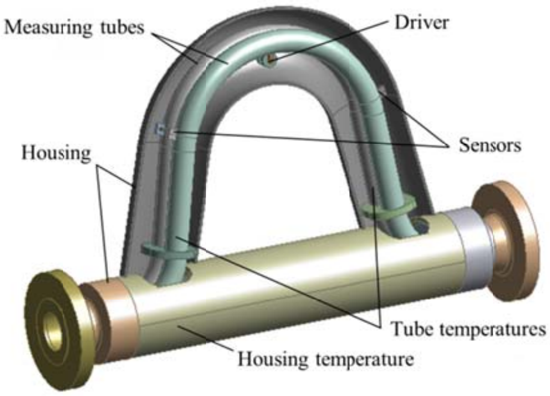

Figure 2: Internal construction of Promass Q.

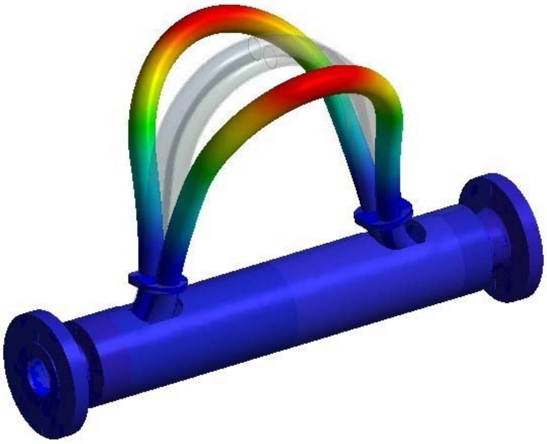

Figure 3: Magnified displacement of balanced working mode calculated by FEM analysis.

3. Meter performance

During the development process FEM and CFD analysis in combination with an experimental approach has been used to optimize sensor design and compensation algorithms. Sensitivities to process variables, fluid properties as well as environmental and installation effects have been minimized to increase temperature and density accuracy. The stated maximum measurement error for temperature is ±0.1 °C $\pm 0.003 \cdot T_m$. Across a density range of 0 to 2000 kg/m³ and temperature range of 20 °C to 60 °C the maximum density error is ±0.2 kg/m³. Outside this temperature range the density error increases by 0.015 kg/m³ per °C. At elevated pressures additional errors also have to be considered. These specifications are confirmed by recently updated third party test results from H&D Fitzgerald Ltd. and new test results from NEL - TUV SUD Ltd. which are presented in the following sections.

3.1 Fluid property influence tests at H&D Fitzgerald Ltd. (UK)

It is well known that fluid properties like density and viscosity can have an influence on oscillation-type density meters. The influence of these factors has been investigated for 13 different fluids (air, several hydrocarbons, ethanol in water, water, dextrose in water, dimethyl-phthalate and tetrachloroethylene). The tests were performed in a static condition

(25°C and 1 bara) in a temperature-controlled enclosure at H&D Fitzgerald Ltd (Fig. 4). There was no adjustment prior to calibration. The individual expanded uncertainties for each fluid type according to H&D Fitzgerald's UKAS accreditation are indicated by error bars in Figures 5 and 6 below. Several meters of all four line sizes have been tested yielding similar results.

To preserve linearity and stability across density ρ, a key design consideration is the correct placement of bracing devices along the measuring tube. Test results in Figure 5 verify that this design step was successfully supported by FEM analysis [2]. Starting with air at 1.38 kg/m^3 and proceeding with tests of different hydrocarbons, ethanol in water, water, dextrose in water, dimethyl-phthalate up to tetrachloroethylene with a density of 1612 kg/m^3, the density deviation stays within ±0.2 kg/m^3.

Measurement of accurate density for viscous fluids is a challenge as higher viscosity fluids transfer shear forces, so more fluid material is accelerated near the tube wall during tube oscillation. The result is a higher density reading than actually present. Using a patented technique fluid viscosity η is estimated and this signal is used to compensate for this effect. Figure 6 shows test results obtained also at H&D Fitzgerald Ltd. [2]. The density deviation stays within ±0.2 kg/m^3 for all fluid viscosities tested up to 2885 mPa·s.

Figure 4: Test installation of three Promass Q DN50 in H&D Fitzgerald's temperature-controlled chamber [2].

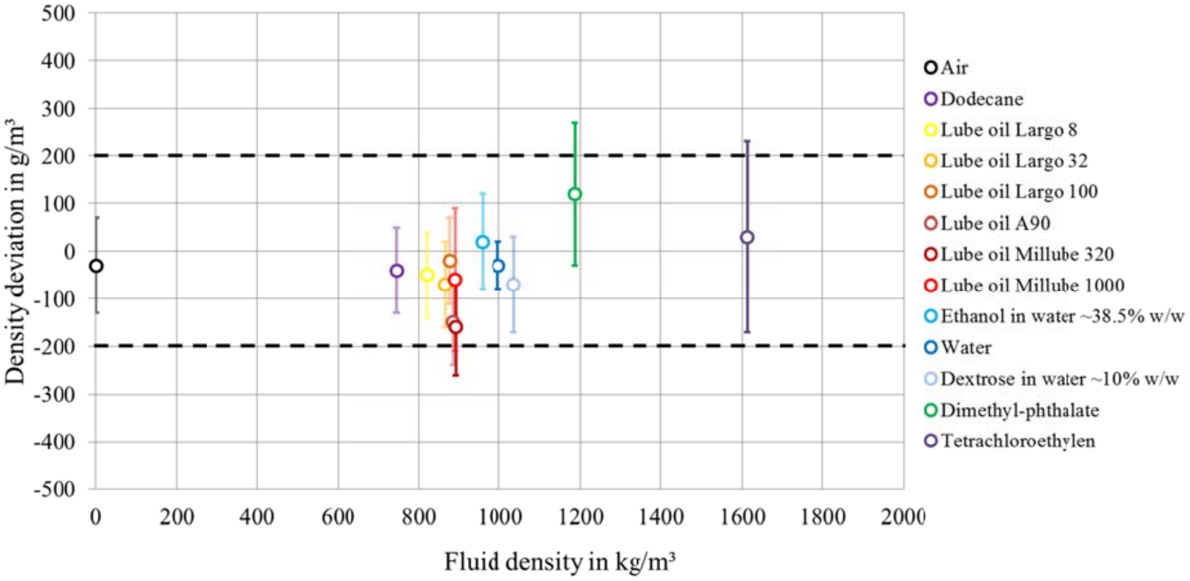

Figure 5: Measured density deviation across varying fluid density with stationary fluid, 25 °C and 1 bara stays within ±0.2 kg/m³ [2].

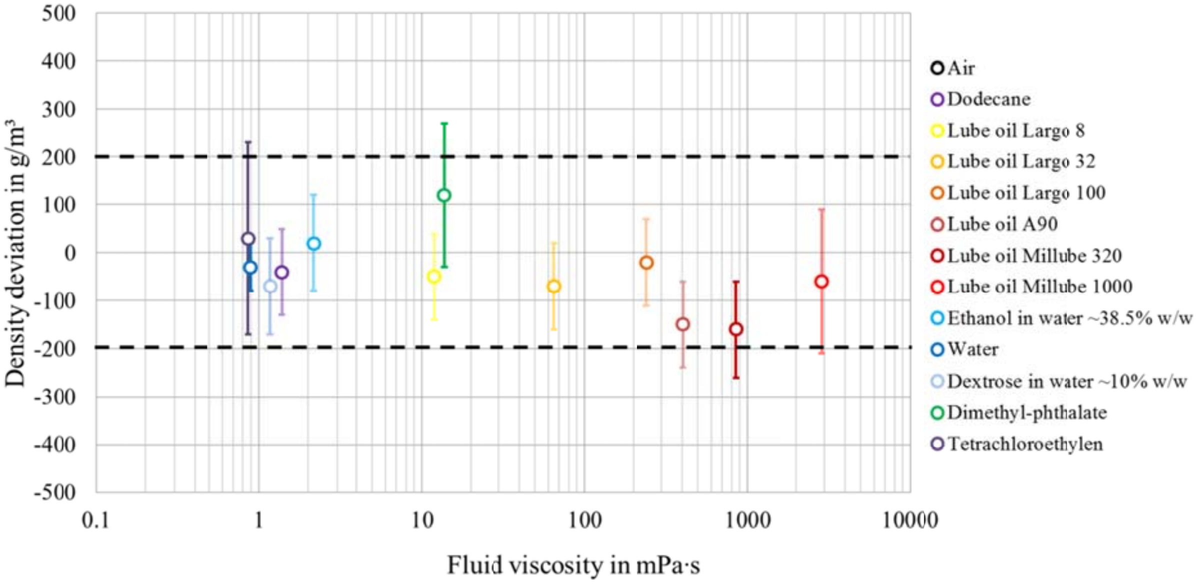

Figure 6: Measured density deviation across varying fluid viscosity with stationary fluid, 25 °C and 1 bara stays within ±0.2 kg/m³ [2].

3.2 Process and environment influence tests at NEL - TUV SUD Ltd. (UK)

3.2.1 Setup and verification

To test the performance of the meter's temperature and density readings at combined elevated temperatures and pressures as well as across a broad range of densities, an extended test matrix has been applied at NEL's density test facility. In the first test sequence three fluids (iso-octane: 642…708 kg/m³, iso-butanol: 751…816 kg/m³ and water: 972…1004 kg/m³) were tested across a combination of five temperatures (10, 25, 40, 60 and 80 °C) and seven pressures (5, 10, 15, 35, 55, 75 and 95 bara) applied simultaneously. Ambient temperatures were controlled to be equivalent to the fluid temperature. Under these conditions the expanded test rig uncertainties in the determination of temperature, pressure and density of the transfer standard fluid used are estimated to be 0.012°C, 0.018 bar and 0.02% (0.2 kg/m^3 for water at ambient temperature and pressure). The second test sequence utilized water at 5 bara with combinations of five fluid temperatures (10, 25, 40, 65 and 90 °C) and three ambient temperatures (10, 25 and 40 °C), resulting in significant temperature gradients across the device in an effort to better replicate common in field application conditions. During the entire test there was an appropriate flow rate guaranteed to ensure a representative and homogeneous fluid sample in the device under test.

A nominal 2 inch Promass Q 500 together with a Cerabar S PMP71 pressure transducer for external pressure compensation were vertically mounted in NEL’s temperature-controlled chamber (see Figure 7). There were no adjustments to the system before, during and after the test. An air-check performed before and after the test disclosed a small negative density shift. Subsequent analysis showed the same shift for liquids. This irreversible shift occurred over the first 7 test points and no further shift was observed for the remaining 121 test points, confirming the stability of the device after the initial shift. By modifications in the production process of the meters, this effect will be avoided in the future. Data shown in chapter 3.2.2 and 3.2.3 were corrected for this density shift.

This example reveals that doing an air-check is an excellent way to verify the meter calibration. Similar to lab densitometers this off-line method helps to detect coating (wax build up, for example) as well as corrosion or abrasion of the measuring tubes. In addition to the air-check the Heartbeat Technology diagnostic feature allows tracking of these slow changes in meter integrity on-line [4]. Within the scope of predictive maintenance the device can be cleaned or recalibrated in time to ensure credibility of the density measurement.

Figure 7: Test installation of Promass Q 500 DN50 (top) with Cerabar S PMP71 pressure transducer (bottom) vertically mounted in NEL's temperature-controlled chamber.

3.2.2 Combined fluid temperature and pressure test results

Due to the direct contact between fluid and tube, tube temperature T_m in principle follows fluid temperature. Accurate tube temperature measurement is the dominant factor for good density measurement because this temperature is used to compensate for the dependency of Young's Modulus and hence stiffness, on temperature for measuring tubes. PT1000s sensors are used to minimize drifts caused by connecting cables. In the meter design phase CFD modelling has been used to study convection effects and finally determine the best possible location and fixation technique for two RTDs, shown in Figure 2. The introduction of both inlet and outlet tube temperature sensors gives a mean tube temperature if the temperature distribution along measuring tube is inhomogeneous due to certain reasons, e.g. a very low flow speed or environmental temperature gradients. In addition, it provides measurement redundancy and greater reliability. Figure 8 shows that the measured temperature deviations across fluid temperature and pressure stay well within the temperature specification. Figures 9, 10 and 11 depict the corrected density deviations across combined fluid temperature and pressure, which remain within specification for all three fluids [3].

Tube shape as well as the location and size of special braces that are located on the measuring tube was carefully optimized by FEM simulation and thoroughly tested to result in as low pressure sensitivity as possible. The small systematic and linear pressure effect that remains of typically -0.030 kg/m^3/bar has been found to be very repeatable. This innovation was achieved by a very reproducible manufacturing process which guarantees roundness and shape of the measuring tubes. For on-line compensation, pressure was read in from the external Cerabar S pressure transducer via current input, resulting in a minimized pressure effect for all three tested fluids, as shown in Figures 9, 10 and 11 [3]. Please keep in mind that a small pressure effect remains, thus the density specification limit depicted in Figures 9, 10, 11 and 12 has to be extended, which is not done here for readability purposes.

The first test sequence also includes dynamic transition zones when pressure or temperature has been changed. After a change it takes time until the test rig stabilizes. The transient behaviour of the density reading from the device under test is shown in Figure 12. Even after significant fluid temperature changes the meter immediately shows a stable and accurate density reading and never leaves the specified accuracy limits. The blue circles mark the stationary sample points which correspond to the measurement values depicted in Figures 9, 10 and 11.

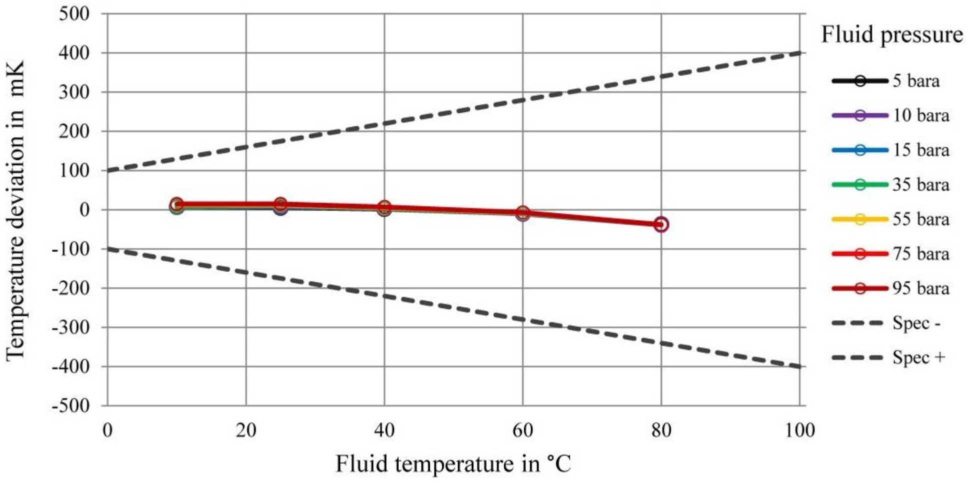

Figure 8: Measured temperature deviation across varying fluid temperature and pressure stays within specification ±0.1 K ±0.003 $\cdot T_m$.

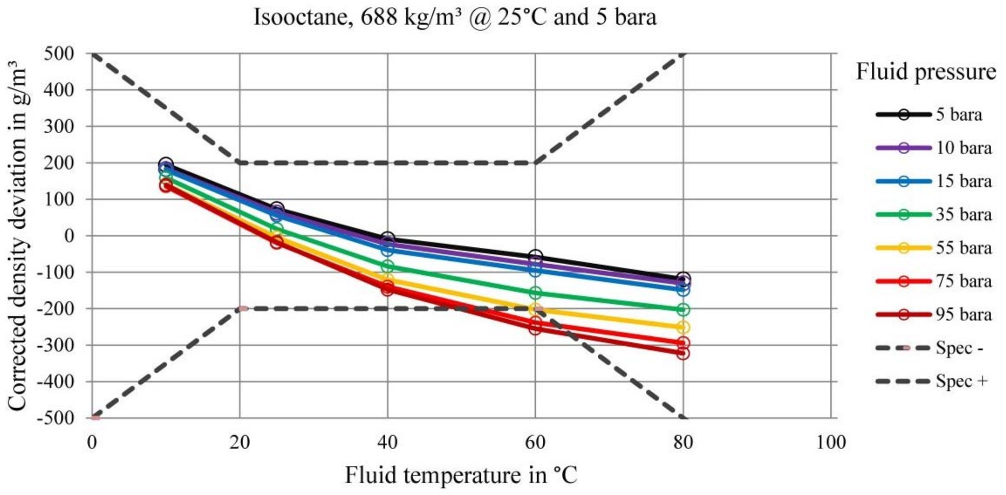

Figure 9: Corrected density deviation for iso-octane (642…708 kg/m³) across varying fluid temperature and pressure stays within specification ±0.2 kg/m³ ±0.015 kg/(m³ °C) outside 20 … 60 °C.

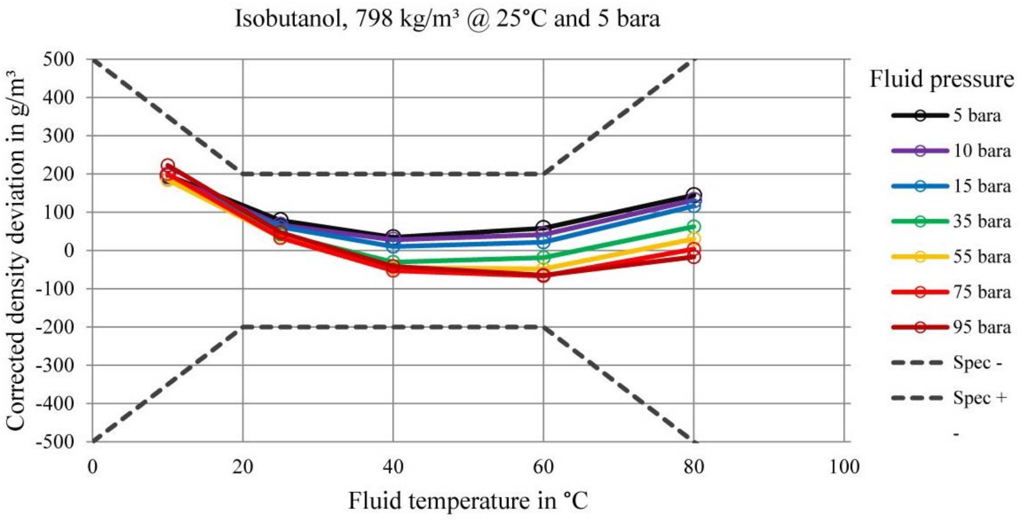

Figure 10: Corrected density deviation for iso-butanol (751…816 kg/m³) across varying fluid temperature and pressure stays within specification ±0.2 kg/m³ ±0.015 kg/(m³ °C) outside 20 … 60 °C.

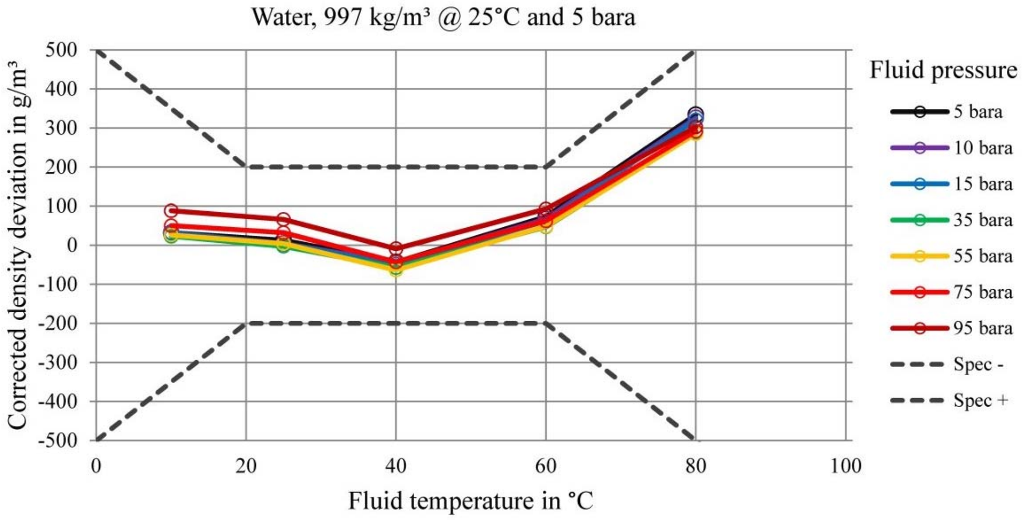

Figure 11: Corrected density deviation for water (972…1004 kg/m³) across varying fluid temperature and pressure stays within specification ±0.2 kg/m³ ±0.015 kg/(m³ °C) outside 20 … 60°C.

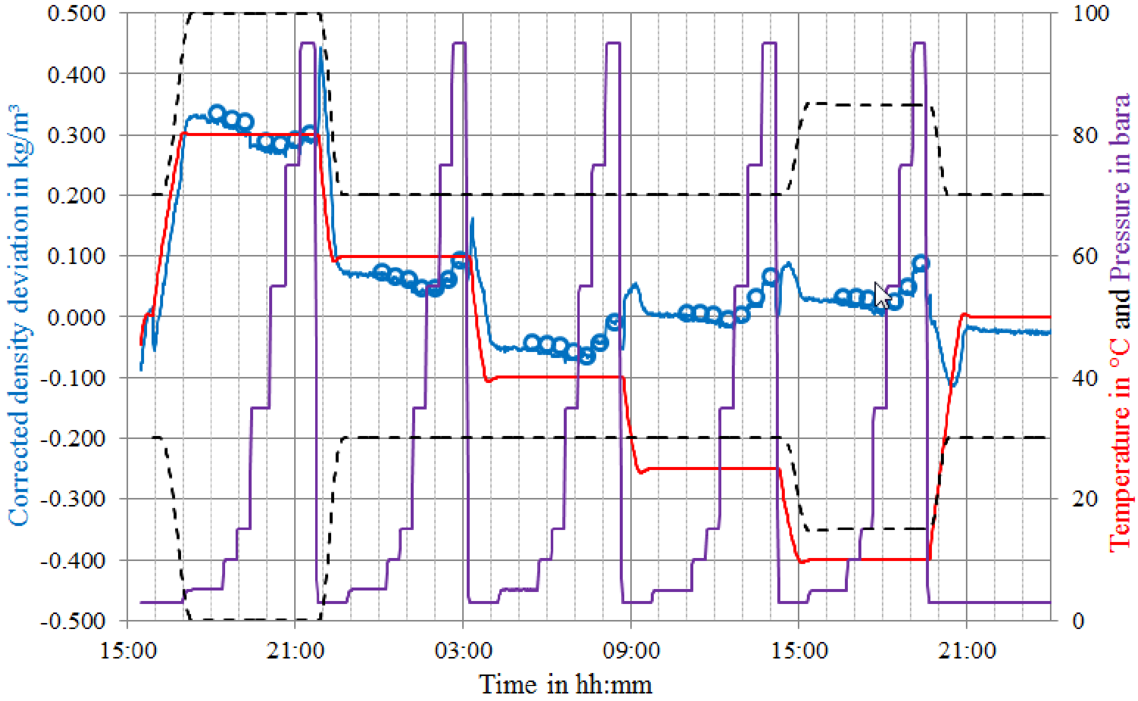

Figure 12: Dynamic behavior of corrected density deviation (blue) for water (972…1004 kg/m³) across varying fluid temperature (red) and pressure (purple) stays within specification ±0.2 kg/m³ ±0.015 kg/(m³ °C) outside 20 … 60 °C (dashed black) even in the transition zones.

3.2.3 Environmental temperature gradient test results

Other environmental aspects such as thermal effects can also affect temperature and density readings. The challenge here is that the meter housing temperature T_h is influenced by sunshine, ambient temperature and convection, and therefore its distribution is seldom homogeneous. Furthermore tube temperature T_m and housing temperature T_h often are different in real applications. These gradients imply thermal stress in the measuring tubes, which in the case of Promass Q have been reduced by optimized tube shape. Residual effects are compensated by ideal placement of an RTD within the housing. FEM and CFD simulation in combination with an experimental approach was a key factor in determining RTD placement at the design phase. In this test sequence the fluid and ambient air temperature have been varied independently, resulting in high temperature gradients. For ambient temperature variations between 10 °C, 25 °C and 40 °C both the temperature and density readings of the meter stay within specification as shown in Figures 13 and 14.

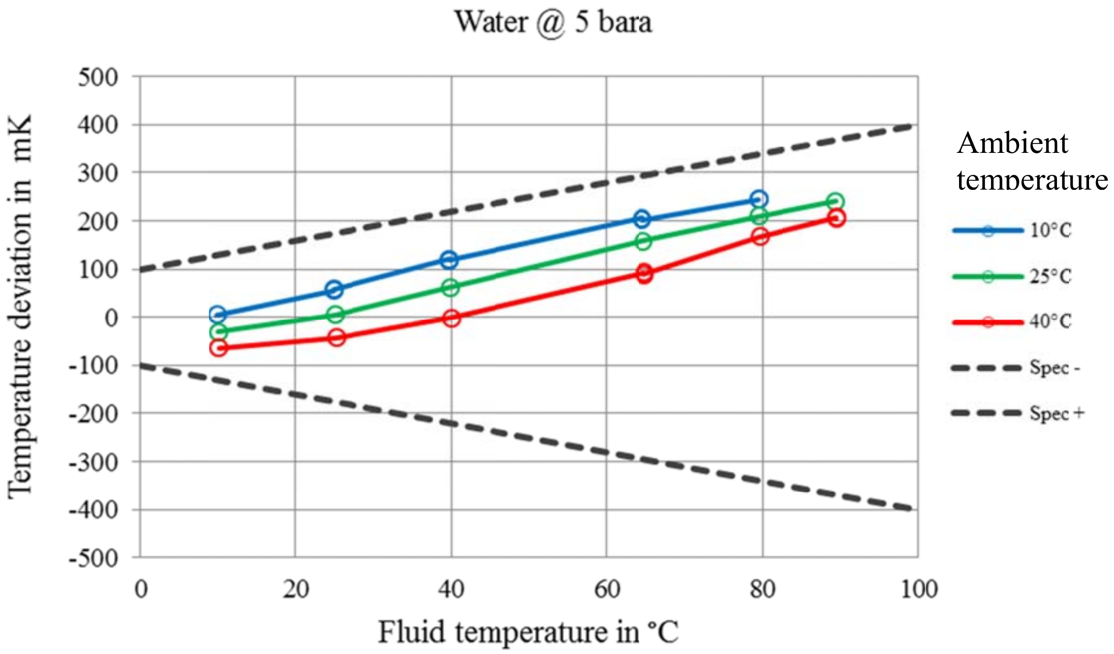

Figure 13: Measured temperature deviation across varying fluid and ambient temperature as a parameter stays within specification ±0.1 K ±0.003 ·T_m.

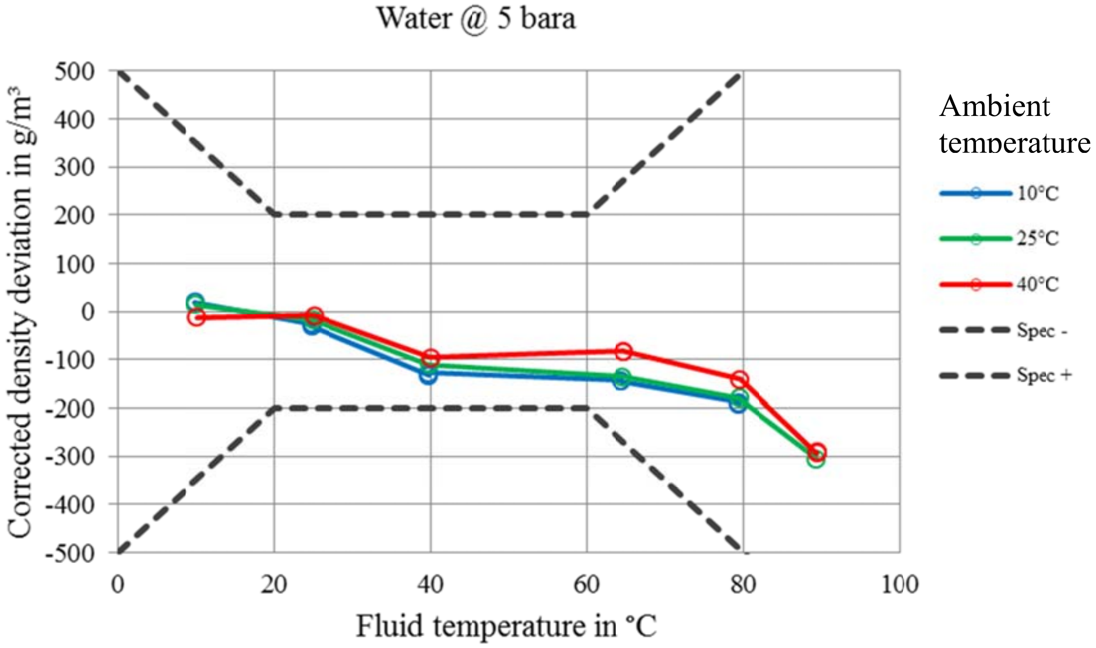

Figure 14: Corrected density deviation for water (972…1004 kg/m³) across varying fluid temperature and ambient temperature as a parameter stays within specification ±0.2 kg/m³ ±0.015 kg/(m³ °C) outside 20 … 60 °C.

4. Conclusion

A new type of Coriolis mass flow meter has been presented. Among other highlights it brings precise fluid temperature and density measurement which is desirable for many applications in the hydrocarbon processing industry. It has been outlined how all aspects of the meter design were optimized to ensure robust temperature and density performance in the field. During the development process FEM and CFD simulation in combination with an experimental approach have been used. This results in a superior out of the box measurement performance. Finally, the meter was third part tested at H&D Fitzgerald Ltd. and NEL - TUV SUD Ltd. to independently confirm the temperature and density specifications of ±0.1°C and ±0.2 kg/m³ respectively across a broad range of process parameters, fluid properties as well as environmental and installation conditions. These successful test results - collected under widely differing conditions as compared to laboratory calibration conditions - provide confidence in the meter designs' ability to provide adequate density measurement performance for key applications found in industry.

References

[1] R. C. Baker, *"Flow measurement handbook: industrial designs, operating principles, performance, and application"*, Cambridge University Press, 2000.

[2] UKAS calibration certificate number 15586; Calibration certificate nn15588, H&D Fitzgerald Ltd., St. Asaph UK, 2016, http://www.density.co. uk/

[3] Certificate No: 2017_336, NEL - TUV SUD Ltd., East Kilbride Glasgow UK, 2017, http://www.tuvnel.com/

[4] Endress+Hauser Flowtec AG, *"Heartbeat Technology™ - Reliable and flexible proof testing"*, http://www.endress.com/en