Endress+Hauser
People for Process Automation

Development process and third party test results of a Coriolis mass flowmeter with superior density performance

Coriolis metering in general is favoured over older mechanical based technologies such as orifice, positive displacement and turbine metering. In addition to mass flow, this multi-variable process meter also determines density, temperature and in some cases even viscosity. A new type of Coriolis mass flowmeter is presented which combines the tremendous technological progress of recent years. Among other highlights, such as new lows for both zero point and the pressure drop, which equates to highest usable flow range and drastic improvements in measurement performance in applications where entrained gas is present, the focus of this paper is on fluid density measurement. The exceptional density measurement performance under real world process conditions is ideally suited to serve the highly demanding application of volumetric custody transfer in the oil and gas industry. Another application is high end concentration measurement in the food and beverage industry. It will be explained how all aspects of the meter design have been optimized to ensure robust density performance in the field. These include tube shape, excellent temperature measurement as well as the most advanced compensation techniques for temperature, pressure, flow and viscosity effects. During the design process FEM and CFD simulation were heavily used. This results in superior out-of-the-box density measurement performance. The meter has been tested internally for the influence of fluid temperature, ambient temperature and pressure as well as under various installation conditions. Finally the meter was third party tested at 25 °C with tubes hanging downwards and verified to be within the stated ±0.2 kg/m³ specification over a broad range of densities and viscosities.

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1. Introduction

Coriolis metering in general is favoured over older mechanical based technologies such as orifice, positive displacement and turbine metering. In addition to mass flow, this multi-variable process meter also determines density, temperature and in some cases even viscosity. Precise density measurement performance under real world process conditions is the basis for the highly demanding applications of volumetric custody transfer and meter proving in the oil and gas industry as well as high end concentration measurement in the food and beverage industry. This is because volume flow is equal to mass flow divided by density and concentration is a function of density. After a brief introduction in to meter properties and working principle, a detailed overview of sensitivity and accuracy is given. It will be explained how all aspects of the meter design have been optimized to ensure robust density performance in the field.

2. Flowmeter

In Figure 1 the design of Endress+Hauser Proline Promass Q 300 is shown. The light-weight, compact and drainable Coriolis mass flowmeter is offered with all industry standard process connections in four different line sizes from 1" to 4". Process temperature and pressure ranges are -196 °C to 205 °C and 0 bar to 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. The transmitter control algorithm generates a harmonic tube vibration at resonance frequency and constant amplitude via an electrodynamic driver at the tube center and two electrodynamic sensors at the tube inlet and outlet, thereby compensating tube damping.

The working principle of Coriolis mass flowmeters has been described in many publications, e.g. [1]. Tube resonance frequency f_r depends on tube stiffness, tube mass and fluid mass load. The fluid density reading ρ is derived from measured raw resonance frequency f_r by

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

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

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

where f, p, v and γ are compensated frequency, process pressure, flow velocity and orientation angle respectively. ρ_r, T_m, T_h, C_0 and C_1 are raw density, mean measuring tube temperature, housing temperature and two calibration constants. η and c are the fluid viscosity and fluid speed of sound.

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

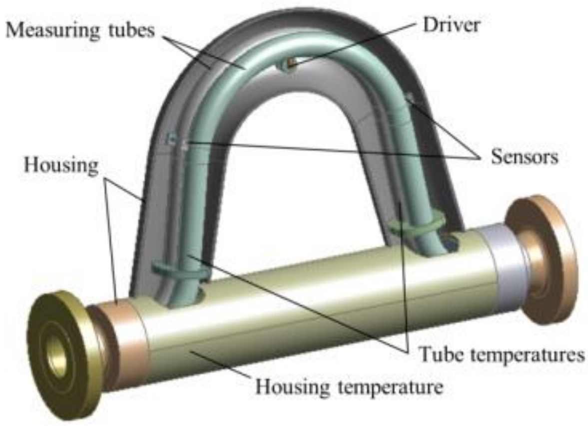

Figure 2: *Internal construction of Proline Promass Q.*

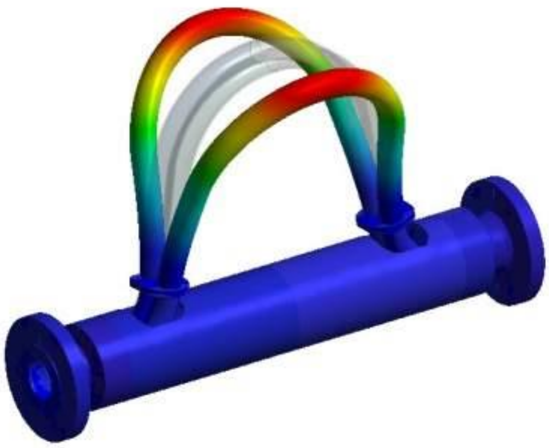

Figure 3: *Magnified displacement of balanced working mode calculated by FEM analysis.*

3. Sensitivity and accuracy

During the development process FEM and CFD analysis were used in symbiosis with an experimental approach in order to optimize sensor design and compensation algorithms. Sensitivity to process variables, fluid properties as well as environmental and installation effects have been minimized to increase density accuracy.

3.1 Process influences

3.1.1 Fluid temperature

Due to the direct contact, the tube temperature T_m in principle follows the temperature of the fluid. Accurate tube temperature measurement is the dominant factor for good density measurement because it is used to compensate the dependency of Young's Modulus or stiffness upon temperature for the measuring tubes. PT1000 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 for any reason the temperature distribution along measuring tube is inhomogeneous, e.g. a very low flow speed or environmental temperature gradients. In addition, it provides a redundant measurement and greater reliability. Figure 4 shows measured density deviation which is within ±0.2 kg/m³ from 20 °C up to 150 °C. Figure 5 gives the specified or maximum expected absolute density deviation as a function of process temperature.

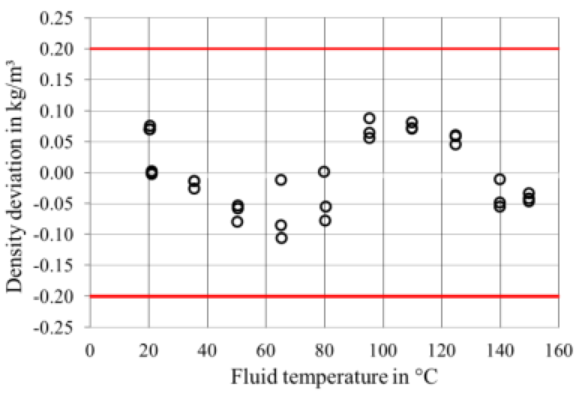

Figure 4: *Measured density deviation as a function of fluid temperature at constant ambient temperature 25 °C: the deviation lies within ±0.2 kg/m³*

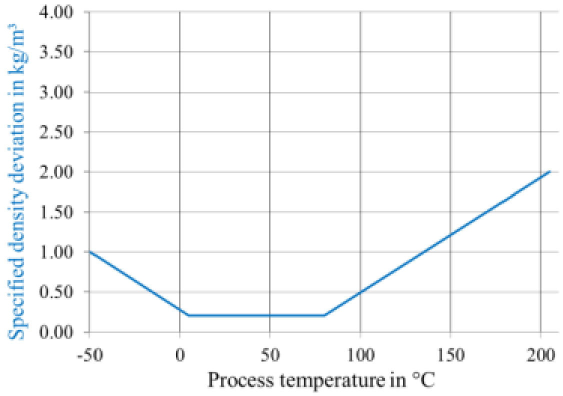

Figure 5: *Specified density deviation as a function of process temperature.*

3.1.2 Process pressure

Tube shape and the location and size of special braces that are located on the measuring tube was carefully optimized by FEM simulation and thoroughly tested in order to have as low a sensitivity to pressure p as possible. The small residual effect has been found to be very repeatable - also another critical aspect. Obviously it is ideal to have the lowest possible pressure effect but the residual effect can easily be compensated if it is repeatable and linear, as shown in Figure 6. This innovation was achieved by the use of hydro-formed tubes. This process guarantees the roundness of the tubes and a very repeatable process in manufacturing. For on-line compensation, a pressure can be manually specified by the operator or read in from an external pressure sensor. Figure 6 shows a specified pressure sensitivity of typically -0.015 kg/m³/bar and the density deviation after compensation by external pressure input. From 0 bar to 100 bar the measured density deviation is linear and within ±0.2 kg/m³.

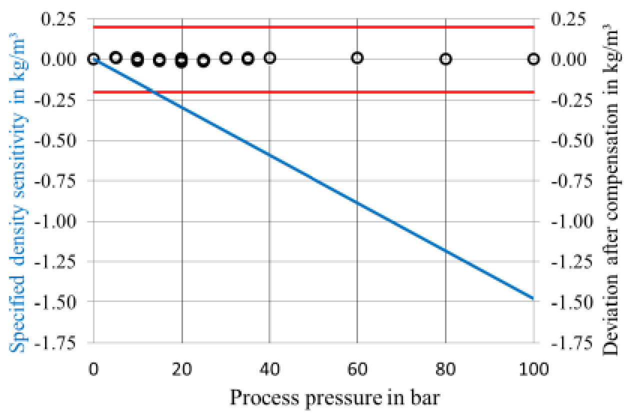

Figure 6: *Specified density deviation and density deviation after compensation as a function of process pressure with water at room temperature.*

3.1.3 Flow velocity

In order to reach this high level of density accuracy, a minimum flow velocity v must be present to guarantee a homogeneous sample in the measuring tube. At high mass flow rates another flow velocity v effect has to be taken into account. At bent tube sections, flowing material generates centrifugal forces, stiffening the tube and increasing tube frequency. As the flow velocity v can be derived from the measured mass flow, internal compensation is possible.

3.2 Fluid properties

3.2.1 Fluid density

In order to ensure a linear density deviation as a function of fluid density ρ in a homogeneous measuring tube, attachments have to be placed very carefully. The test results shown in Figure 7, obtained at UKAS-accredited laboratory of H&D Fitzgerald Ltd., verify that this design step was successfully supported by FEM analysis [2]. For 11 different fluids at 25 °C, starting from air at 1.38 kg/m³ through various hydrocarbons, ethanol in water, water, dextrose in water, dimethylphthalate up to tetrachloroethylene at 1612 kg/m³ the density deviation stays within ±0.2 kg/m³. Several meters of all line sizes were tested and gave similar results. More details concerning the uncertainties of measurement with the calibrants can be found in the certificates.

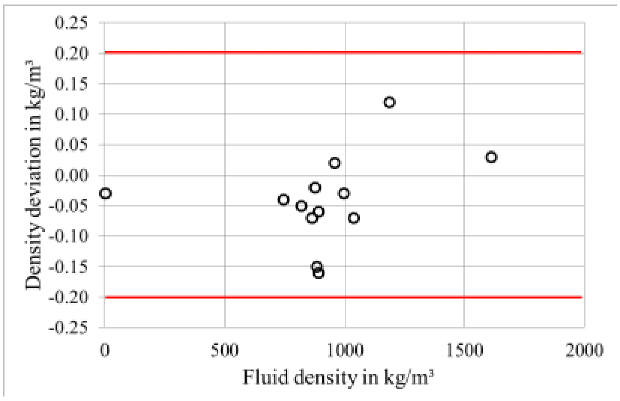

Figure 7: *Measured density deviation as a function of fluid density at 25°C in accordance with H&D Fitzgerald Ltd. certificate number 15215 & nn15217R: the deviation stays within ±0.2 kg/m³ [2].*

3.2.2 Fluid viscosity

An accurate measurement of density for viscous fluids is a challenge as they transfer shear forces. This results in more fluid material being accelerated near the tube wall during tube oscillation. The result is a higher density reading than true. Using a patented technique, fluid viscosity η is estimated by measuring tube damping and this information helps to compensate for the effect. Figure 8 shows test results obtained at UKAS-accredited laboratory of H&D Fitzgerald Ltd. Up to a viscosity of 2885 mPa·s density deviation stays within ±0.2 kg/m³. Several meters of all line sizes were tested and gave equivalent results. More details concerning the uncertainties of measurement with the calibrants can be found in the certificates.

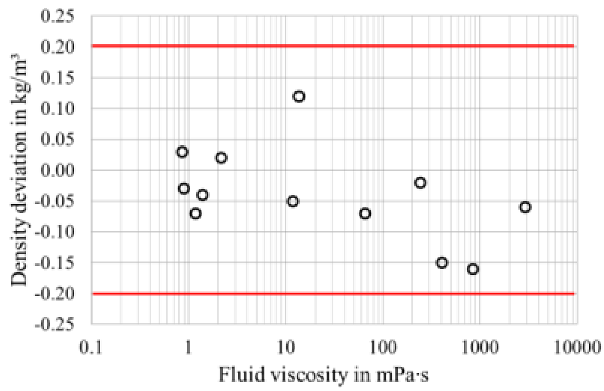

Figure 8: *Measured density deviation as a function of fluid viscosity at 25 °C in accordance with H&D Fitzgerald Ltd. certificate number 15215 & nn15217R: the deviation stays within ±0.2 kg/m³ [2].*

3.2.3 Fluid compressibility and entrained gas

Liquids typically exhibit a rather small compressibility, hence the speed of sound c is high. If gas is entrained in liquid, the compressibility of the mixture increases significantly. Due to this compressibility effect, fluid amplitude is higher than tube amplitude and as a consequence the fluid density is apparently higher. By simultaneously driving a higher order tube resonance frequency, the velocity of sound of the mixture can be estimated and the density deviation can be eliminated completely. Details on this new and patented technology, called MFT, can be found in [3].

3.2.4 Corrosion, abrasion and coating

In some applications corrosion, abrasion and deposits are issues. As these effects occur gradually over time the density reading becomes permanently and systematically wrong and is not noticed by the operator. The new diagnostic feature Heartbeat Technology allows these slow changes in meter integrity to be monitored and tracked [4]. When indicated within the scope of predictive maintenance, the device can be cleaned or recalibrated to ensure continued credibility of the density measurement. Moreover, by using Heartbeat Technology the meter can be replaced before a pending tube rupture or cleaning can be commissioned before it becomes clogged.

3.3 Environmental and installation effects

3.3.1 Environmental temperature and radiation

An additional challenge is that meter housing temperature T_h in general is influenced by sunshine, ambient temperature and convection, therefore its temperature distribution is seldom homogeneous. Furthermore, the measuring tube temperature T_m and the housing temperature T_h often are different in real applications. These gradients produce thermal stress in the measuring tubes, which has been reduced by optimizing the tube shape. Residual effects are compensated by ideal placement of one RTD on the housing. FEM and CFD simulation in combination with an experimental approach was key factor in this design phase. In Figure 9 the ambient temperature T_a changes between 10 °C and 50 °C. Density variation is negligible and within ±0.2 kg/m^3. Similar results have been obtained in direct sunshine.

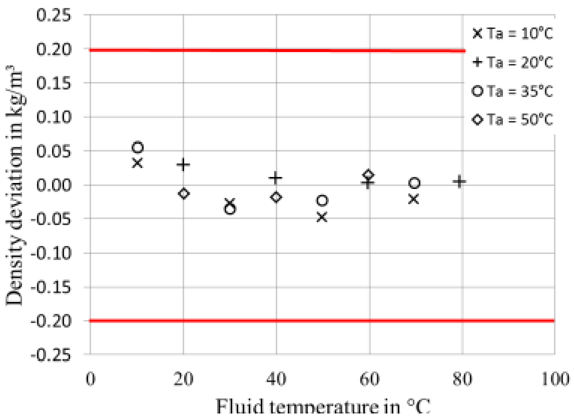

Figure 9: *Measured density deviation as a function of water temperature for various ambient temperatures.*

3.3.2 External forces and vibrations

Tube shape and housing stiffness have also been optimized so that the density measurement is insensitive to external installation stress. At the same time the overall meter size and weight have still been kept comparatively compact and light. The moderate driving frequency resulted from the moderate tube height still offers great immunity against the influence of disturbing external vibrations which are typically at low frequencies.

3.3.3 Meter orientation

To a very small extent all bent tube Coriolis mass flowmeters are prone to gravitational effects. Depending on meter orientation angle γ with respect to the earth's gravity, tube mass gives rise to tension or compression along the tube, slightly changing resonance frequency and density reading. By entering this angle γ after meter installation, this effect is corrected automatically by a patented algorithm.

4. Conclusion

A new type of Coriolis mass flowmeter has been presented. Among other highlights, it brings precise fluid density measurement which is desirable for many applications in the process industry. It has been explained how all aspects of the meter design were optimized to ensure robust density performance in the field. During development process FEM and CFD simulation in symbiosis with an experimental approach were used. This results in a superior out-of-the-box density measurement performance. Finally the meter was tested both internally as well as by a third party and verified to be within the stated ±0.2 kg/m^3 specification across a broad range of process parameters, fluid properties as well as environmental and installation conditions.

References

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

[2] UKAS calibration certificate number 15215; Calibration certificate nn15217R, H&D Fitzgerald Ltd., St. Asaph UK, 2016, http://www.density.co. uk/

[3] H. Zhu, A. Rieder, Y. Lin, "*An Innovative Technology for Coriolis Metering under Entrained Gas Condition*" in *Conference Proc.* FLOMEKO 2016, Sydney AU, 2016. https://www.metrology. asn.au

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