

Development of a mass flowmeter based on the Coriolis acceleration for liquid, supercritical and superfluid helium

de Jonge T.[#], Patten T.^{*}, Rivetti A.⁺ and Serio L.

LHC Division, CERN, 1211 Geneva 23, Switzerland

[#]Emerson Process Management, 6341 Baar, Switzerland

^{*}Micro Motion, Inc., Boulder (CO), US

⁺IMGC-CNR, Istituto di Metrologia “G. Colonnetti”, Torino, Italy

Beginning in the 1980's, Coriolis meters have gained generalised acceptance in liquid applications with a worldwide installed base of over 300,000 units. To meet the demands of cryogenic applications below 20 K, off-the-shelf Coriolis meters have been used, with minor design modifications and operational changes. The meters were originally calibrated on water and tested on liquid helium at 4.5 K, supercritical helium around 5 K and superfluid helium below 2 K. The meters maintain their intrinsic robustness and accuracy of better than 1% of measured value; accuracy is independent of density and temperature.

INTRODUCTION

Large cryogenic facilities for accelerator and fusion superconducting devices (cavities, magnets, power lines and current leads) require accurate process monitoring, thermal performance evaluation and correct distribution of cooling power. Robust, accurate and reproducible mass flow measurements enhance the ability to perform these functions effectively. Cryogen mass flow metering [1] has usually been performed by indirect measurements at ambient temperature or by laboratory-type differential pressure devices (Venturi or orifice), because true cryogenic meters have not been commercially available. Coriolis mass flow meters have been successfully used for more than 20 years to meter flow of liquids and gases at ambient temperatures when robustness, good accuracy and long-term reproducibility were required. Newer design have shown greatly improved low-flow sensitivity, lower pressure drop and immunity to noise; factors which now enable their successful use in the gas phase as well as in cryogenics applications.

WHY CONSIDER CORIOLIS FLOW METERS?

Unlike traditional flow measuring techniques, Coriolis meters respond directly to mass flow. Eliminating the need for density compensation has been a breakthrough for end-users. Consequently, Coriolis flow meters have contributed to reduce the purchased and operating costs and to reduce the overall uncertainty for flow measurement systems.

Traditional flow measurement technologies require rigorous installation procedures to deliver optimum performance, specifically with regard to inlet flow conditioning. Straight runs of pipe and/or flow conditioners are often used to ensure that the system meets performance expectations. Coriolis based metering systems do not require straight runs of piping and flow conditioners because the meters do not rely on a predictable fluid velocity profile to measure flow. Eliminating the need for additional piping and/or flow conditioners helps to reduce the overall cost of the metering system. For skid-based metering systems, decreasing the overall piping requirement helps to reduce the overall size of the system.

Coriolis meters do not experience a time-dependent drift in their performance [1]. In a clean fluid such as liquid helium, performance is unlikely to deteriorate because the structure of the tube cannot change. Since the meter's flow measurement is ultimately a function of the tube vibrations, which in turn are functions of the structure of the tube, signal will not drift for a given tube. Most Coriolis meters are manufactured of stainless steel, which is mechanically very stable in helium service; thus, there are no changes in tube properties [2], and therefore calibration, over time.

For many years, turbine meters and differential pressure devices have been the accepted and preferred flow measurement technologies for low-temperature helium applications [3]. In most situations, especially when thermal performance or cooling power need to be assessed, mass-flow rate is the preferred parameter. A density measurement is therefore required in conjunction with the flow measurement to calculate mass flow. Furthermore, in order to obtain accuracies of the order of few %, expensive and complicated calibrations at working temperatures need to be performed.

Coriolis meters are simply made of two vibrating parallel tubes, are calibrated in water, measure directly the mass flow rate, are intrinsically robust, work with remote electronics up to 1 km distance (radiation environment), can reach absolute accuracy of better than 0.25 % and reproducibility of 0.2 %.

PRINCIPLE OF OPERATION

A Coriolis meter requires two components: an in-line sensing element and a transmitter that interprets the signals from the sensor and converts the signals into useable outputs, usually pulse, analog (4 - 20 mA), and digital outputs (Figure 1). The sensing element usually consists of a manifold that splits the flow into two parallel tubes (low-range meters are usually composed of a single tube). The tubes are vibrated at a resonant frequency of the system, similar to a tuning fork. As the flow passes through the tubes the fluid momentum coupled with the oscillatory motion created by the vibration induces a Coriolis force along the length of the tubes. This force translates into a phase shift (or Δt) along the length of the tube (Figure 2). The Δt is directly proportional to mass flow rate. Two electromagnetic sensors are located on opposite legs of the flow tubes; the vibration of the tubes generates sinusoidal signals on the pickups that are shifted in phase due to the Coriolis force. The transmitter measures the Δt between the two sinusoidal signals and mass flow rate is calculated.



Figure 1 Coriolis meter sensor and transmitter

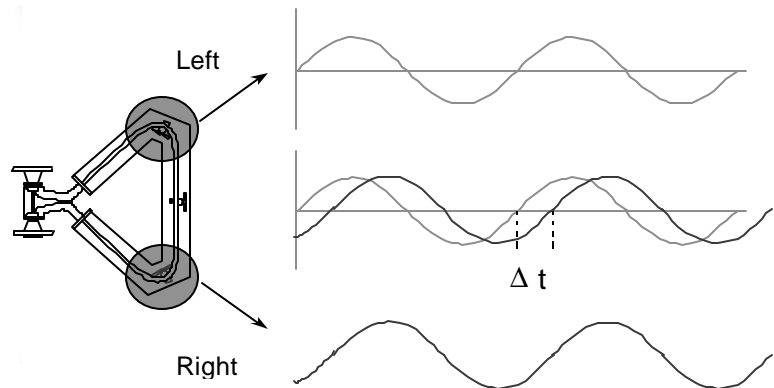


Figure 2 Coriolis flow meter operation

When the stainless steel flow tubes change temperature, the material properties change slightly. At temperatures below ambient Young's modulus increases, which in turn increases the stiffness of the tube. Normally, the manufacturer mounts a PT100 (RTD) to the flow tube and the temperature compensation is performed automatically for each meter.

Because Coriolis meters are insensitive to fluid parameters (i.e. swirl, viscosity, density, etc.) they are successfully used in a remarkably wide range of applications. This paper specifically discusses the application on liquid, supercritical and superfluid helium, but the meters are used extensively on: all fluid phases (gas, liquid, critical-phase fluids), a wide temperature range (from 700 K down to few K), and a

wide pressure range (up to 350 bar). The meters tested and used by CERN have tube diameter size of 2, 6 and 20 mm, but Coriolis meters are manufactured with diameter sizes up to 300 mm.

DESIGN CHANGES FOR CRYOGENIC USE

The meters built for liquid and supercritical helium (between 4 K and 6K) applications at CERN were standard meters with few modifications.

A typical Coriolis meter makes a temperature measurement for compensation of the vibration characteristics of the sensing element. The change in modulus of elasticity is well characterised [2] and the modulus of elasticity can be corrected at various operating temperature.

For cryogenic applications the effect on modulus of elasticity is non-linear to approximately 30 K. For liquid helium temperatures below 20 K the change of modulus is very small. Therefore the temperature measurement is not required and a constant calibration factor is applied.

Normally during calibration of a Coriolis meter the effect of temperature is incorporated directly into the calibration constants. Since the temperature measurement is not used in this case, an alternative method is required for the compensation. The modulus of elasticity is constant with a value of approximately 207.5 GPa below 20 K; by recording the calibration temperature (usually water at approximately 20°C where the modulus is 194.6 GPa) the correction factor is easily calculated: $207.5/194.6 = 1.066$.

One important requirement for CERN is component robustness and reliability. The specific requirement for the flow meter was the ability to cycle at least 10 times between ambient and operating temperature (4 K). Thermal cycling was conducted on prototype meters over the temperature range to prove robustness and there was no indication of any pressure-containing component issues. However, it was found that small gauge wire internal to the sensor sometimes broke resulting in electrically open circuits, therefore causing meter failures. The wire gauge was increased, and meters were found to survive at least 60 thermal cycles over the same temperature range.

The last change was rather simple and obvious. All meters are purged with an inert gas to ensure a good hermetic, dry seal for the electronic components. Nitrogen or argon are typical, but these freeze at 4 K. The meter was therefore purged with helium to eliminate this issue. This makes also a secondary containment for the process fluid. Alternatively it can be left open to the cryostat insulation vacuum.

Coriolis meters can reach absolute accuracy as low as 0.25 %, the limiting factor being the accuracy of measurement of the Young's modulus (about 1 %), and impressive reproducibility (better than 0.2 %) over a large turn down ratio (1:100). Accurate measurements (few %) can be obtained up to 1:1000 turn down ratio, allowing precise measurements with reasonable pressure drop (Figure 3 and 4).

TESTING AND VALIDATION PROGRAM

Several tests facilities were employed in order to assess performance, characteristics, and limitations, if any, of the manufactured Coriolis flowmeters.

The flow meters assembled and calibrated in water at the manufacturer's premises were then tested at ambient temperature (pressure, leak tightness) before shipment.

The performance (accuracy, reproducibility, pressure drop, zero stability) at nominal working conditions (supercritical helium at 5 K and 0.3 MPa) was first assessed in a test cryostat built and designed at CERN [1]. The following step was to test the flowmeter accuracy to metrological standard in a calibration module of absolute type, designed and built at IMGC (Italy) [4], with accuracy of better than 0.5 % in liquid, superfluid and supercritical helium, between 1.7 K and 20 K. Figure 3 and 4 summarize the tests performed on two sizes of meters at various temperatures and helium fluid state (liquid, supercritical and superfluid). The final accuracy of the meters depends on the zeroing procedure in the lower range and in the accuracy of the measurement of the Young's modulus. The offset of about 1.2 % of both meters is due to the measurement error of the Young's modulus at low temperatures [2].

The Young's modulus for SS 316 L at 5 K can therefore be more precisely defined by our measurements to be 205 +/- 1 GPa.

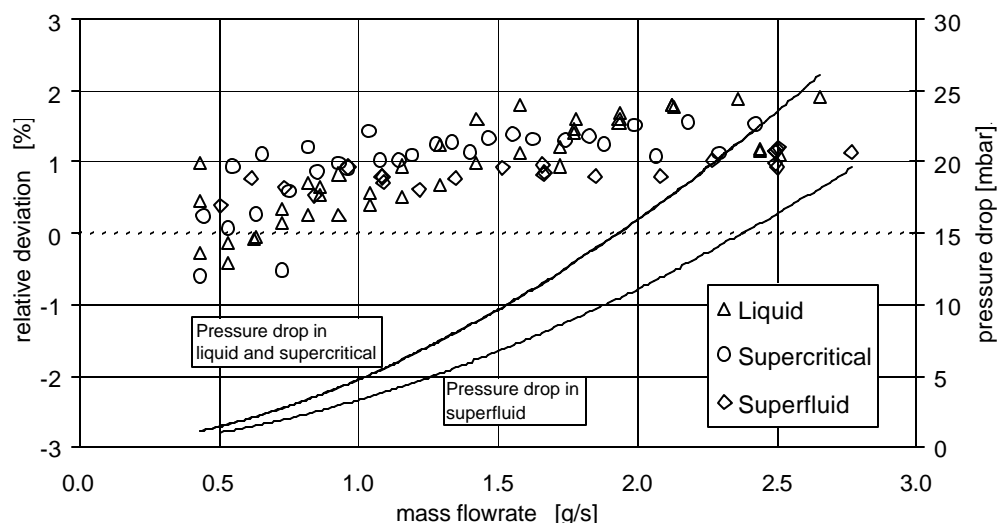


Figure 3 CMF010 (2 mm size, 60 g/s f.s.) Coriolis flowmeter: relative deviation of measured value with respect to calibration module and calculated pressure drop vs. mass flow

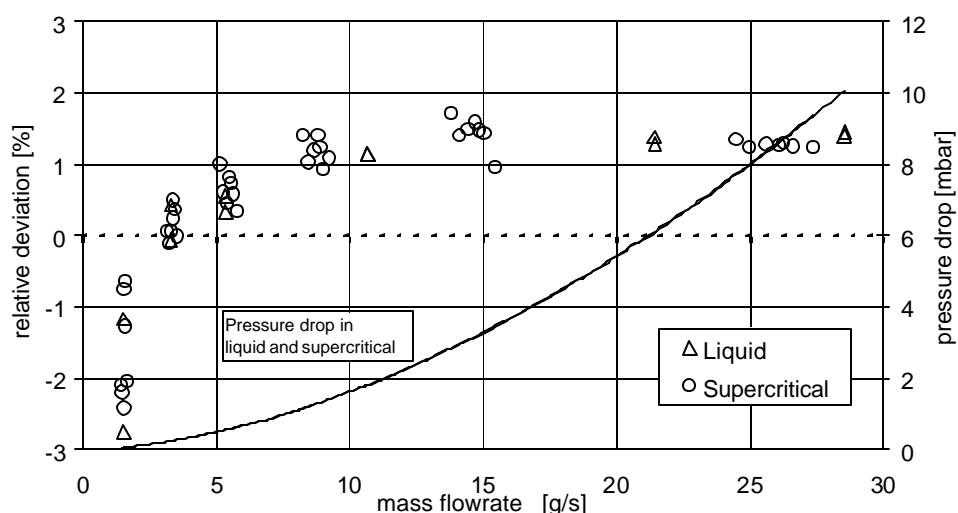


Figure 4 CMF025 (6 mm size, 140 g/s f.s.) Coriolis flowmeter: relative deviation of measured value with respect to calibration module and calculated pressure drop vs. mass flow

CONCLUSIONS

Coriolis flow meters have been extensively and successfully tested with cryogenic helium down to 1.7 K and show superior performance in terms of absolute accuracy, repeatability and robustness. The meters were calibrated on water and tested on liquid and supercritical helium, indicating a high degree of insensitivity to fluid properties. Several flow meters ranging from 0.5 g/s up to 1.2 kg/s are now installed and successfully operating in CERN cryogenic test facilities to assess performances of superconducting devices, liquid helium pumps and to meter cryogenic cooling power distribution.

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