VSL

National Metrology Institute

MetHyInfra

New insights on LH2 flow measurement uncertainty

Federica Gugole

How large is the measurement uncertainty of a Coriolis flow meter calibrated with water at ambient conditions (T=295 K) but used to measure liquid hydrogen (T=20 K) ?

Uncertainty budget: starter pack

1. Equation(s) of the mass flow through a Coriolis mass flow meter
2. Knowledge on the physical quantities affecting the measurements
3. Information on material properties and associated uncertainty

To construct a comprehensive budget, we need to link the physics to the material properties

There are several equations available describing the physical principle behind the measurements given by Coriolis flow meters (CFM)

Not all equations have explicit dependency of the flow rate measurement on critical material properties such as the Young's modulus

We found two equations with explicit dependency on the elastic properties of the steel:

- Raszillier and Durst (1991) give an equation for the flow through a straight tube CFM
- Costa et al (2020) derived an equation for the flow through a U-shape CFM

Equation of the mass flow rate in a straight tube CFM (shown to be applicable to more complex geometries)

$$Q_m = \frac{C}{\gamma\left(\frac{x_L}{L_p}\right) L_p^3} E(T)\, I_p\, \Delta t$$

where

- Q_m : mass flowrate
- $E(T)$: Young's modulus
- $I_p = \pi\left(r_o^4 - r_i^4\right)/4$: moment of inertia of the pipe
- r_o , r_i : outer and inner radii of the pipe respectively
- C : a constant number
- Δt : time delay detected by two sensors on the tube
- $\gamma\left(\frac{x_L}{L_p}\right)$: a function of the sensor location x_L in relation to the length of the pipe L_p (can be treated as a constant)

VSL National Metrology Institute

MetHyInfra

Equation of the mass flow rate through a U-tube CFM → Here the flow depends also on the Poisson's ratio!

$$Q_m = \frac{3\pi E(T)\left(r_o^4 - r_i^4\right)}{32SL^3}\left[1 + \frac{4L^2}{3W^2(\nu(T)+1)} - \frac{\pi\beta_1^4 W}{12L}\right]\Delta t$$

where

- S : dimensionless shape parameter
- L : length of the flow tubes
- W : width of the bend
- $\nu(T)$: Poisson's ratio
- $\beta_1 \approx 1.8751$: first order solution to the cantilever beam mathematical model

Figure taken from Costa et al. (2020)

There are quite some aspects to consider
Some of them are easier to correct for than others

CFM measurements are affected by

- Temperature
- Pressure
- Reynolds number
- Multi-phase of the fluid being measured

CFM measurements are said not to be affected (at first order) by

- Installation effects
- Flow profile
- Fluid properties

Temperature is one of the main factors influencing measurement result and uncertainty

MetHyInfra

Temperature affects three quantities determining the meter measurements:

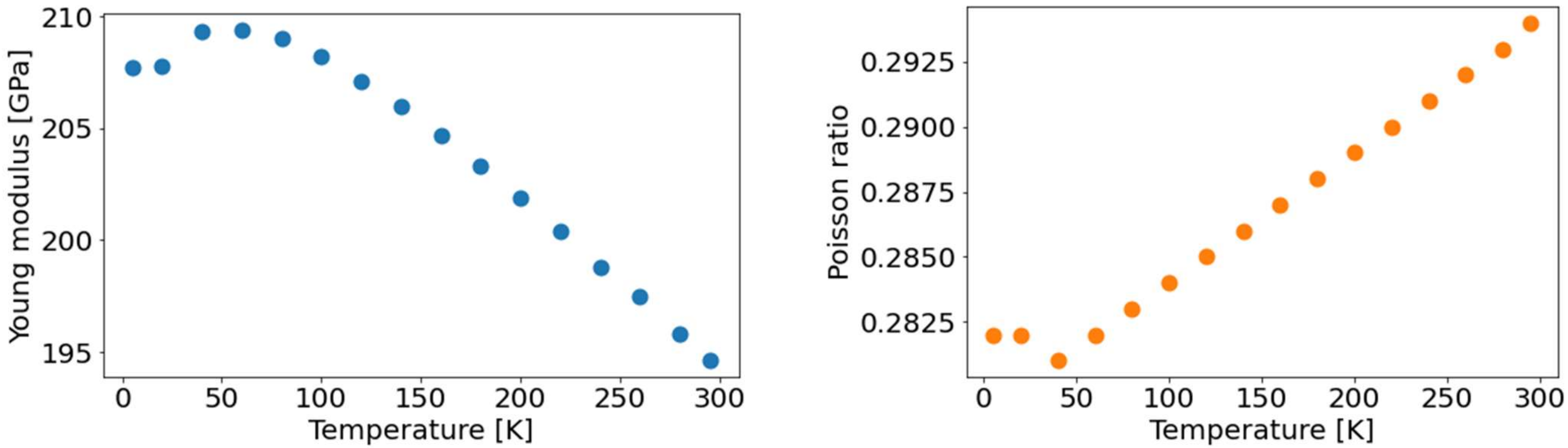
- Elastic properties of the steel
  - Young’s modulus
  - Poisson’s ratio
- Linear thermal expansion coefficient

Uncertainties in the temperature measurement cause extra uncertainty in the temperature sensitive quantities

The flow meter temperature measurement can be affected by the thermal insulation of the meter (Standiford 2021)

Elastic properties of steel at cryogenic temperatures have been measured only once … 40 years ago …

Ledbetter (1981) measured the elastic properties of stainless steel 304, 310 and 316 for temperatures between 5 K and 295 K. We could not find more recent measurements.



Measurements of the Young's modulus and Poisson's ratio for stainless steel 316 reported by Ledbetter (1981).

… and their associated uncertainty is unclear

Ledbetter (1980) *Metal Science* reports U=1% for Young's modulus, and U=1.5% for the Poisson's ratio of stainless steel 304, 310, 316

Ledbetter et al (1980) *Journal of Applied Physics* instead reports U=0.5% for the Young's modulus and Poisson's ratio of stainless steel 304

In both Ledbetter's (1980) papers it is not clear what the reported values are; Ledbetter talks about "variations" (*MS*) and "imprecisions" (*JAP)*

Partial agreement between the two papers if we assume that Ledbetter et al (1980) *JAP* reported standard uncertainty, while Ledbetter (1980) *MS* reported expanded uncertainty (k=2)

Values reported by Ledbetter (1980) *MS* could be a worst-case scenario, but the reality might be different

A conservative approach would be to assume that the values reported by Ledbetter et al (1980) *MS* are expanded uncertainties and propagate them forward

Ledbetter et al (1980) *MS* say that all possible variation sources are included (e.g., chemical composition, sample anisotropy, etc …)

If the Coriolis meter is being calibrated at ambient temperature, some sources of uncertainties can be excluded

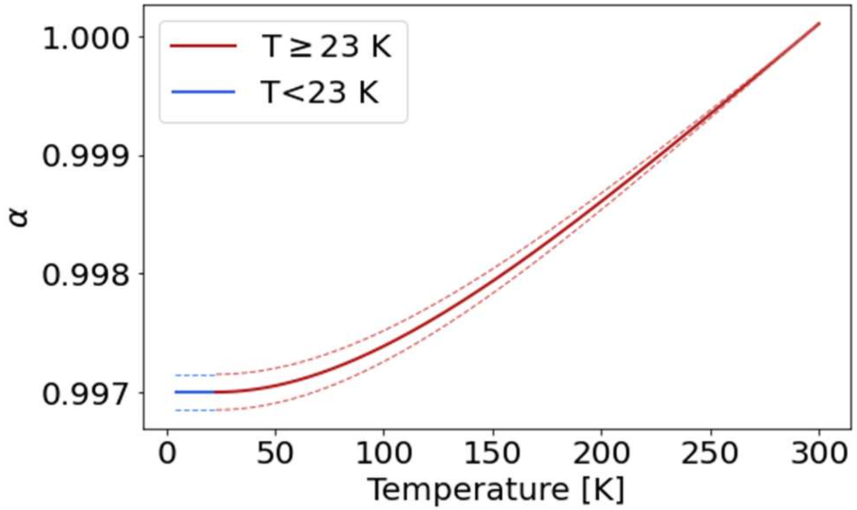
However, there is no (public) information regarding the uncertainty contribution of the single sources

NIST provides a polynomial fit (with uncertainty) of the thermal expansion coefficient for 4 K≤ T ≤300 K

It is unclear how this polynomial fit has been obtained

It is unclear also which data had been used and what was the uncertainty on the data

According to NIST, the thermal expansion coefficient is constant for T < 23 K



The effect of pressure is easier to correct Following manufacturers specifications is an option

Wang and Hussain (2010) found a difference between theoretical and experimental data with pressure sensitivity coefficient in general agreement with manufacturer's specifications

Wang and Hussain (2010) note also that the newer generation of CFM have a reduced pressure sensitivity with respect to the previous generation meters

Mills (2020) reported a linear effect due to pressure and, similarly to Costa et al. (2020), found a correction factor matching the manufacturer's specifications

Büker et al. (2020) did not find any pressure dependence when testing small size CFMs in a high-pressure test facility

Depending on the Reynolds number of the flow there might be an extra (easy-to-correct) source of error

Huber et al. and Mills (2020) showed that the CMF measurements present a dependency on the Reynolds number

Compensation can be done by measuring the viscosity of the fluid

Uncertainties in the viscosity measurement should be included in the total uncertainty budget

Figure taken from Huber et al.

The effects of measuring a two-phase fluid are harder to estimate and further studies might be necessary

MetHyInfra

Levien (1993) states that if the gas-content is “large”, i.e., > 5%, sloshing takes place, which adds complex damping terms “and the like”

Hemp and Kutin (2006) calculated the fractional error E_d in fluid density measurement and the fractional error $E_{\dot{m}}$ in mass flow reading due to compressibility of the fluid

$$E_d = \frac{-2\alpha}{1-\alpha} + \frac{1}{4}\left(\frac{\omega_1}{c} b\right)^2 \quad ; \quad E_{\dot{m}} = \frac{-2\alpha}{1-\alpha} + \frac{1}{2}\left(\frac{\omega_1}{c} b\right)^2$$

- ω_1 : actual resonance frequency of vibration
- b : inner diameter of flow tube
- c : speed of sound in two-phase fluid
- α : gas volume fraction

National Metrology Institute

Some assumptions were made to get those error estimates; further research required to remove them

Meter errors have been calculated assuming:

- $f_i \gg f_1$; where f_i is the resonance frequency of transverse fluid vibrations, and f_1 is the frequency of operation of a Coriolis meter
- The distribution of bubbles is assumed to be uniform within the flowmeter
- The meter has a straight tube design
- The velocity profile is flat

Meter errors due to relative motion of the bubbles and liquid have been ignored

Damping effects in two-phase fluids in vibrating tubes have not been investigated

Basse (2014) presented a theoretical generalization of those error estimates for a general two-phase fluids

Basse (2014) reports more generalized equations for E_d and $E_{\dot{m}}$

$$E_d = \frac{\alpha(\rho_f - \rho_p)(1-F)}{\alpha\rho_p + (1-\alpha)\rho_f} + \frac{1}{4}\left(\frac{\omega}{c}b\right)^2$$

$$E_{\dot{m}} = \frac{\alpha(\rho_f - \rho_p)(1-F)}{\alpha\rho_p + (1-\alpha)\rho_f} + \frac{1}{2}\left(\frac{\omega}{c}b\right)^2$$

where

- ω : driver frequency
- $F = 1 + \frac{4(1-\tau)}{4\tau - \frac{9iG}{\beta^2}}$: reaction force coefficient
- ρ_f : density of the continuous fluid (e.g., water)
- ρ_p : density of the particles entrained in the main fluid (e.g., air, sand, oil)

Little should be done regarding effects due to installation or fluid properties

Costa et al. (2020) and Jonge et al. (2002) say that CFM are insensitive to fluid properties

Huber et al. mention that CFM is independent of flow profile and installation effects

Levien (1993) notices that external masses added to the tubing may upset the proportionality of frequencies → this can be corrected by adjusting the fixed masses

Because of second order effects, Levien (1993) states that reasonable (tube vibration) amplitude control is necessary

VSL

Summing up

MetHyInfra

Changes in temperature lead to a change in the Young's modulus, Poisson's ratio and thermal expansion coefficient

The pressure compensation factor specified by the manufacturers can be relied on when computing adjustments in the measurements due to pressure

Correction due to the Reynolds number can be easily applied

There is a theoretical correction for multiphase hydrogen flow; however, this does not consider effects due to the meter being a physical entity

Fluid properties, flow profile and installation should not affect the measurements of the Coriolis mass flowmeter (at least at first order)

VSL

Data availability looks good … but not too good.

MetHyInfra

Factor contributing to measurement uncertainty	Source where relevant data / info can be found
Corrected Young's modulus and Poisson's ratio	Ledbetter 1981: table with values of the elastic constants at 16 different temperatures; measurement uncertainty unclear
Pressure effect correction	Meter specification from manufacturer
Thermal expansion coefficient	NIST website, Material Properties: 316 Stainless
Water based calibration uncertainty	Data obtained during calibration
CMF meas. uncert. due to, e.g., linearity, hysteresis, …	Data obtained during calibration
Temperature meas. uncert.	Depends on sensor being used; data obtained during calibration
CMF zero stability	(Ideally) Zeroing performed under actual cryogenic conditions
CMF repeatability	Type A

VSL

References (1)

- H. Raszillier, F. Durst (1991), *Coriolis-effect in mass flow metering*
- T. Wang, Y. Hussain (2009), *Coriolis mass flow measurement at cryogenic temperatures*
- F. O. Costa, J. G. Pope, K. A. Gillis (2020), *Modeling temperature effects on a Coriolis mass flowmeter*
- D. Standiford (2021), *Calibration is the key*
- H. M. Ledbetter (1981), *Stainless-steel elastic constants at low temperatures*
- H. M. Ledbetter, N. V. Frederick, M. W. Austin (1980), *Elastic-constant variability in stainless-steel 304*, Journal of Applied Physics
- H. M. Ledbetter (1980), *Sound velocities and elastic constants of steel 304, 310, and 316*, Metal Science
- NIST website, *Material properties: 316 Stainless*, https://trc.nist.gov/cryogenics/materials/316Stainless/316Stainless_rev.htm
- T. Wang, Y. Hussain (2010), *Pressure effects on Coriolis mass flowmeters*

MetHyInfra

References (2)

- C. Mills (2020), *Calibrating and operating Coriolis flow meters with respect to process effects*
- O. Büker, K. Stolt, M. de Huu, M. MacDonald, R. Maury (2020), *Investigations on pressure dependence of Coriolis mass flow meters used at hydrogen refueling stations*
- C. Huber, M. Nuber, M. Anklin, *Effect of Reynolds number in Coriolis flow measurement*
- T. de Jonge (2002), T. Patten, A. Rivetti, L. Serio, *Development of a mass flowmeter based on the Coriolis acceleration for liquid, supercritical and superfluid helium*
- A. Levien (1993), *Basic principles for vibrating tube Coriolis mass flow sensor design*
- J. Hemp, J. Kutin (2006), *Theory of errors in Coriolis flowmeter readings due to compressibility of the fluid being metered*
- N. T. Basse (2014), *A review of the theory of Coriolis flowmeter measurement errors due to entrained particles*

MetHyInfra

Internal

Physikalisch-Technische Bundesanstalt Braunschweig und Berlin

CESAME exadébit SA

Justervesenet

METAS

RISE Research Institutes of Sweden

TÜV SÜD National Engineering Laboratory

VSL Dutch Metrology Institute

external

Thermodynamik Ruhr Universität Bochum RUB

University of Ljubljana Faculty of Mechanical Engineering

esi get it right® MECAS ESI s.r.o.

Imperial College London

MAXIMATOR® Maximum Pressure.

DNV

Perfection in fluids. The right flow by German engineering. ep-e.com

Ingenieurbüro T. Steuer its-tech.de

Bronkhorst® Flow Technology

This project (20IND11 MetHyInfra) has received funding from the EMPIR programme co-financed by the Participating States and from the European Union's Horizon 2020 research and innovation programme.

EMPIR EURAMET

The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

MetHyInfra

Federica Gugole

fgugole@vsl.nl

Data Science & Modelling

VSL