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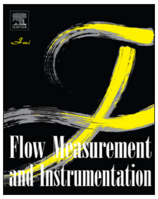

Calibration of an ultrasonic flow meter for hot water

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ABSTRACT

If we want to keep the number of necessary characterisation measurements within acceptable limits, we need to be confident that a flow instrument design reacts in a predictable and straightforward way to systematic influences. In this paper, the important systematic influences for an ultrasonic flow meter (UFM) for feed water flow are identified to decide which characterisations have to be carried out in addition to a typical baseline calibration with water at 20 °C. In heat metering applications where there are temperatures up to 120 °C it is for example known that the temperature influence on the flow instrument is important and this also applies to higher temperatures such as in the feed water control of power plants. One of the critical systematic temperature influences that affects most flow instruments is the thermal expansion of the meter body. From June 2009 to March 2010, the "Heat and Vacuum" department of the Physikalisch-Technische Bundesanstalt conducted a measurement campaign to characterise the influence of thermal expansion of a meter body on the calibration of an 8 inch (DN 200) five chord UFM for feed water application in the temperature range from 4 °C to 85 °C and flow range from 50 $m^3\,h^{-1}$ to 900 $m^3\,h^{-1}$. An overview of the procedures and facility used for the calibration is given and the measurement conditions under which the calibrations were performed are detailed. It is shown that a linear model of the thermal expansion effect is appropriate for the investigated conditions.

1. Introduction

The research on flow instrument performance to date has tended to focus on flow profile effects more than temperature effects, mainly because precision flow calibration facilities for high temperatures are expensive to operate and therefore scarce. Table 1 gives an overview of currently available calibration facilities for hot water flow. For feed water applications at 230 °C,8 MPa and 3500 $m^3\,h^{-1}$, there are currently no flow facilities that enable one to reproduce the measuring conditions in the field. Thus, traditional performance testing is not possible. Ultrasonic flow meters (UFM) are affected by systematic physical effects [1]. Mechatronic effects on the ultrasonic transducers lead to the so-called zero point influence [2]. Fluid dynamic properties such as viscosity [3] influence the velocity distribution. The acoustic propagation of the ultrasonic signal depends on the flow velocity u_0 or more precisely the Mach number $\mathrm{Ma} = u_0/c$ (c is the speed of sound). The influence is small for liquids as will be exemplified in Section 1.6. Process temperature and pressure lead to mechanical deformation of the meter body. In the following we will look at the key factors for feed water applications. To experimentally investigate and interpret the influences, we need well-defined and stable operating conditions that can only be achieved in flow laboratories and not on site. It is therefore beneficial to test flow instruments in a dedicated laboratory [4]. Also, the desired uncertainty of flow instruments has reached values of less than 0.5%. Therefore, traceability becomes an important factor, especially if small systematic effects are to be identified.

1.1. Traceability

Traceability is the key to measurement accuracy. A quantitative statement about measurement accuracy is given by stating the measurement uncertainty. Measurement uncertainty consists of random and systematic errors (bias). Random errors can be reduced with good instrumentation and knowledge about the measurement. Systematic errors on the other hand are not found without traceability. To gain confidence in a measurement, traceable calibration measurements are needed. Otherwise inconsistent or even wrong measurements may result. Only an unbroken chain of traceability ensures the accuracy and quality of an instrument. To achieve the required low measurement uncertainties in the process and power plant industry, direct traceability to the official standards by calibration is needed. For this, the national metrology institutes (NMIs) provide standards for the SI units. For mass flow,

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Table 1
List of available calibration facilities for hot water.

Temperature range in °C	Flow in $m^3\ h^{-1}$	Uncertainty ($k = 2$) in %	Laboratory
20–70	12,000	0.08	NMIJ Japan
10–90	900	0.06	SP Sweden
12–80	400	0.1	DTI Denmark
10–85	270	0.13	SMU Slovakia
90–130	180	0.07	BEV Austria
8–90	180	0.05	BEV Austria
5–90	1,000	0.04	PTB Germany
5–230	200	0.4	PTB Germany*
30–85	100	0.4	GUM Poland
19–85	36	0.1	MKEH Hungary
30–90	36	0.3	LNE France
10–70	100	0.1	CMI Czech Rep.

* Under construction.

the primary units are based on measurements of the known physical quantities mass and time. For volume flow, the density also has to be considered (see Section 2.3). The standards of the NMIs are usually of the highest accuracy and therefore only have low random and minimised systematic errors. Only with traceability to these standards, can a measurement uncertainty be stated. There is a distinct difference between traceability to a working standard and traceability to the physical quantity itself. When calibrating flow instruments, often a second flow instrument is used that was calibrated against a primary standard, but this approach may lead to undetected systematic errors. For example, both instruments may be affected by thermal expansion or long term drift and then there will be correlation in the measurement. The standards of an NMI are at the top of the calibration hierarchy and every step downwards results in additional random and systematic errors.

1.2. *Systematic influences and compensation*

In the following, we will describe the key influences that affect the measured velocity of an ultrasonic flow instrument for feed water. Temperature T, pressure p and the Reynolds number Re (see Section 1.4) have to be recognised as major influences. The raw flow rate Q_{UFM} of the ultrasonic flow meter is calculated according to [5] from the measured upstream and downstream ultrasonic travel times of each of the five parallel chords. Afterwards, the flow computer applies a hydraulic factor $k_h(\mathrm{Re})$, based on flow calibration, and theoretical thermal $k_T(T)$ and pressure $k_p(p)$ expansion factors on the raw measured flow rate Q_{UFM} to calculate the flow rate indication Q_i.

$$Q_i = k_h(\mathrm{Re})\,k_T(T)\,k_p(p)\,Q_{\mathrm{UFM}}. \tag{1}$$

1.3. *Flow disturbances*

The uncertainty contribution of disturbed velocity distributions can dominate the total uncertainty budget of ultrasonic flow measurements. This issue is presented in many papers and, thus, not further detailed here. In this measurement campaign, the following known rules are therefore followed. (1) A five chord meter is used that has a smaller sensitivity to flow disturbances. (2) The meter is installed in a meter run package with fixed inlet and outlet sections and a flow conditioner to reduce variation in installation conditions. (3) The meter run package is to be installed in a well-chosen position, preferably behind a reducer. (4) Diagnostic information from the flow meter is used on site to check that velocity disturbances are sufficiently small. As stated by the manufacturer of the UFM, the uncertainty contribution because of flow conditions is, under these conditions, approximately 0.1% [1].

1.4. *Reynolds number*

The desired velocity distributions for pipe flow at the flow rate Q and average velocity u_0 are symmetric about the pipe axis. Because of wall friction, they have near zero velocities at the wall and higher velocities ($1.1u_0$–$1.2u_0$) at the centre. For higher Reynolds numbers $Re = u_0\,D/\nu$, with kinematic velocity ν and pipe inner diameter D, the velocity distributions are more homogeneous because of turbulent mixing. This leads to changes in the hydraulic factor k_h for the UFM. In the investigated Re-range between 1 ñ 10^5 and 4.5 ñ $10^6$$k_h$ changes about 0.15% for this five chord UFM. The influence is less pronounced for high Reynolds numbers. If we extrapolate k_h to process conditions in a feed water circuit, i.e. at $Re = 22$ñ10^6, the change from the measured k_h at $Re = 4.5$ñ10^6 is less than 0.1%. An extrapolation in the Reynolds range is therefore feasible if the flow profile is undisturbed. It is intended to validate this assumption on the high Reynolds calibration facility of NMIJ [6].

1.5. *Water chemistry*

Feed water is purified water with low levels of dissolved minerals to protect boilers and turbines from corrosion and scaling. Chemicals such as hydrazine or ammonia are added to remove excess oxygen or respectively to raise the pH. This so-called conditioning only leads to minimal changes in viscosity and density compared to the wide working range of UFMs for liquids from viscous oils to hot water. The flow facility of PTB that is used in this study also employs conditioned water that is representative of feed water in terms of water quality. On the other hand, substances like magnetite in feed water flows are known to cause deposits leading to deviations of 1% of pressure differential flow instruments [7]. Current research on water chemistry related problems therefore focuses on deposits. There are ongoing efforts to detect drifts caused by deposits with the signal information of ultrasonic flow meters or by using additional independent flow instruments.

1.6. *Acoustics*

Since in this instance the calibration is performed with water with a speed of sound larger than 1400 m s^{-1} and the maximum velocity is smaller than 7 m s^{-1}, the Mach number Ma is always below 0.005. The change of hydraulic factor k_h due to the path trajectory deviation from a straight line is approximated by $\Delta k_h/k_h \approx -\mathrm{Ma}^2$ [8] and is in this case smaller than 25 ppm. In the feed water application, the velocity is below 10 m s^{-1} and the sound velocity is larger than 1000 m s^{-1}. The Mach number will then still be below 0.01 and the resulting error below 0.01%. It does not need to be considered here.

1.7. *Zero point*

The ultrasonic measurement principle is based on measuring travel times of ultrasonic waves in a fluid with a required resolution of picoseconds. Mechatronic effects on the transducers and signal chain such as cabling and amplifiers affect the signal before it even goes through the fluid. The resulting systematic error depends mainly on the change in signal delay time, leading to the so-called zero point error. An exact zero point calibration can only be performed if the fluid is perfectly still and the sound velocity is known exactly. On-site installations and also flow test rigs do not usually fulfil these conditions and special setups are