REYNOLDS DEPENDENCE OF FOUR DIFFERENT FLOW METERS USED FOR FEED WATER FLOW MEASUREMENTS

P. Klason[a*], O. Büker[a], P. Lau[a], O. Penttinen[a], K. Mattiasson[a], T. Lederer[b], K. Tawackolian[b], J. Frederiksen[c], A. K. Niemann[c] and P. Milota[d]
[a]SP Sveriges Tekniska Forskningsinstitut AB, Department of Measurement Technology, Brinellgatan 4, 504 62 Borås, Sweden
[b]Physikalisch-Technische Bundesanstalt (PTB), Department of Heat and Vacuum, Abbestraße 2-12, 10587 Berlin, Germany
[c]Danish Teknologisk Institut (DTI), Department of Energy and Climate, Kongsvang Allé 29, 8000 Aarhus C, Denmark
[d]Bundesamt für Eich- und Vermessungswesen (BEV), Department of Flow, Temperature and Photometry, Arltgasse 35, 1160 Vienna, Austria
***peter.klason@sp.se**

Abstract

In the 'Metrology for improved power plant efficiency' project the Reynolds dependence of four flow meters used for feed water flow measurements were investigated. The four flow meters were ultrasonic, inductive, orifice plate and Venturi tube flow meter. The measurements were performed up to 90 °C to study the temperature dependence of the meters. An extrapolation model up to 230 °C was developed to measure the feed water flow with an uncertainty in the range of 0.3 % – 0.5 %. The influence of a double bend out of plane disturbance on the meters was also investigated. Some meters showed a significant dependence.

Introduction

The feed water flow is one of the most important control parameters in a power plant. However, to measure the feed water is challenging because of the usual operating conditions in a power plant where feed water temperatures above 200 °C, pressures of 8 MPa and flow rates of 1000 L/s are common. There exists no calibration facility in the world that can calibrate a flow meter under these conditions. Hence the flow meters are calibrated under ambient conditions and an additional extra measurement uncertainty is added to the calibration uncertainty. In the best case this additional uncertainty is based on empirical data or experience of the manufacturer.

Another important parameter to be taken into account is that flow meters are sensitive to asymmetries of the flow velocity profile. Disturbances in the velocity profile come from installation effects e.g. upstream pipe bends, but the velocity profiles are also dependent on the water temperature. Hence, all flow meters are temperature dependent and affected by inhomogeneous or changing temperature distribution of the flow. In power plants it is more a rule than an exception that the feed water flow have an inhomogeneous temperature profile. If the velocity profile is fully developed the effect of temperature and installations on the profile can be separated from each other.

Within the 'Metrology for improved power plant efficiency' project a work package was initiated to improve our knowledge and understanding of the behavior of feed water flow meters. The aim is to find a method to extrapolate low temperature calibrations to high temperatures in order to measure feed water flow with an uncertainty in the range of 0.3 % – 0.5 %. The four measuring techniques investigated were orifice plate flow meter, ultrasonic flow meter, electromagnetic flow meter and Venturi flow meter. Four National Metrology Institutes (BEV, DTI, SP and PTB) were involved in this work package, each one investigating one flow sensor. The temperature dependence of the flow meters was characterized and the effect of a double bend out of the plane was also investigated.

Experimental details

Each one of the four participating National Metrological Institutes (NMI) followed a common test plan to perform the measurement. The electromagnetic flow meter was investigated at BEV, the orifice plate at SP, the Venturi tube at DTI and the ultrasonic flow meter at PTB. In addition to this test plan each NMI added extra measurement points during the investigations. An overview of the capabilities of the flow facilities at each NMI can be found in table 1. Since one of the main goals with this project was to determine an extrapolation model, the four flow meters were characterized for Reynolds number up to $1.5*10^6$, by adjusting the temperature and flow rates. The temperature was varied between 10-85 °C to find the temperature dependence for each flow meter.

Table 1. Overview of the calibration and measurement capabilities of the participating laboratories including expanded uncertainty (k=2) [*under construction].

Temp [°C]	Flow [Ls^{-1}]	Uncertainty	Lab.
3-90	50	0.05	BEV
90-130	50	0.07	BEV
3-90	278	0.04	PTB
90-230	50	0.40	PTB*
4-85	139	0.10	DTI
15-85	200	0.06	SP

To study the installations effects, a long straight inlet condition and a disturbed condition were investigated.

For the disturbed case a custom-built flow disturber was constructed to simulate a double bend out-of-the plane. The flow profiles were studied both in the undisturbed and disturbed case as well with Laser Doppler Velocimetry. The measurements were done on the exact place where the flow meters were mounted. These results are presented elsewhere [1].

Ultrasonic flow meter

The 10 beam ultrasonic flow meter (UFM) was characterized at PTB between 10 °C and 80 °C. The inlet section consisted of a 140 *D* long straight pipe where the last 40 *D* of the inlet section consisted of hydraulically smooth pipes. The calibrations were performed using a gravimetric principle, in each test a volume of 17 m^3 was used to fill the balance.

Electromagnetic flow meter

The characterization of the electromagnetic flow meter (EMF) was performed at the BEV test facility. The measurements were done with the gravimetric principle using a 2500 L volume and a 3000 kg scale. The EMF was installed with an inlet section consisting of an NEL (Spearman) flow conditioner [2] followed by a 40 *D* long straight pipe. The temperature was varied between 20 °C and 80 °C.

Orifice plate flow meter

The orifice plate flow meter was characterized at SP using SP's primary test rig. The pipe inner diameter D was 102.26 mm and the nominal bore, d, was 51.13 mm which corresponds to a diameter ratio, β, of 0.5 [3]. The inlet section consisted of a 71 *D* long straight section with a Zanker flow conditioner [2, 4] placed 58 *D* upstream from the orifice plate. The temperature was varied from 20 °C up to 85 °C. As calibration reference a coriolis mass flow meter (CMF) was used as secondary standard for Reynolds numbers up to $8*10^4$. The CMF was calibrated ten times in advance using a 60 L piston prover at the desired test point. For Reynolds number above $8*10^4$ an EMF was used as secondary standard. The EMF was calibrated at the desired test points at least four times in advance using 3.5 m^3 ball prover. The differential pressure was measured with two pressure transmitters connected in parallel for all measurements.

Venturi tube flow meter

The Venturi tube investigated at DTI had a nominal diameter of 100 mm and a throat diameter of 71.49 mm. The corresponding diameter ratio (β) was 0.7149. The pressure was measured over a ring chamber with 4 holes, 6 mm in diameter. A static weighting method was used as flow reference with a 5000 kg scale. The inlet section consisted of a 42 *D* straight pipe section and the outlet of a 12.5 *D* straight pipe section.

Results

The four different flow meters use on different measuring principles. For the UFM and the EMF the principle is based on measuring the flow velocity profile. The volume flow rate is then calculated by multiplying with the cross-section area. The temperature dependence for these two flow meters can be derived and hence the temperature correction is already implemented in the device by the manufacturer. The presented measurement deviation is the deviation from the nominal calibration factor, the K-factor. For the differential pressure flow meters, the Venturi tube and the orifice plate, the measuring principle is based on measuring the static pressure difference between the up- and downstream sides of the flow meter. For both the Venturi tube and the orifice plate the theoretical discharge coefficient as a function of Reynolds number can be found in the ISO-standard [5]. For these two flow meters the presented measured deviation is the deviation from the theoretical discharge coefficient.

Ultrasonic flow meter

The UFM has a correction function implemented in the flow calculator. The correction function calculates the flow rate from the raw data with correction for the dependence of pressure, temperature, flow velocity and Reynolds number. The correction function is given in equation (1),

$$q_v = k_m \cdot k_h(Re) \cdot k_t(T) \cdot k_p(p) \cdot w_{raw} + Q_0 \quad (1)$$

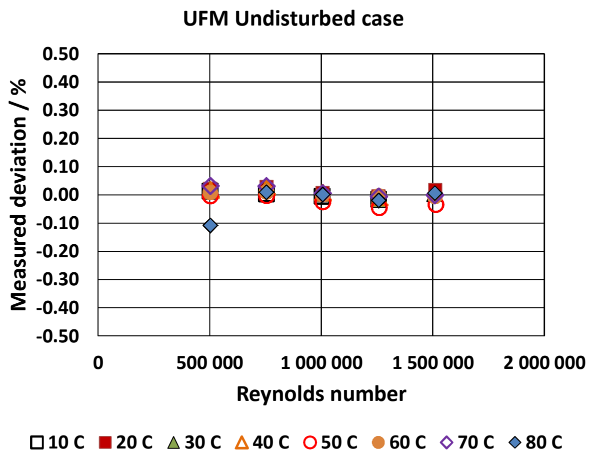

Figure 1. Results of undisturbed measurements: Measurement deviation of the UFM in dependence of Reynolds number at different temperatures.

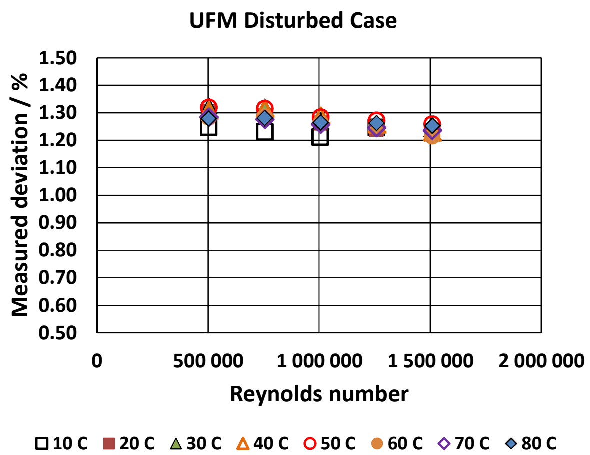

Figure 2. Results of disturbed measurements: Measurement deviation of the UFM in dependence of Reynolds number at different temperatures.

Where k_m is the meter constant given from calibration, k_t is the thermal expansion constant, k_p is the pressure expansion factor which was not used during these experiments since the pressure was kept constant to 0.2 MPa. The hydraulic correction constant k_h was determined by the manufactory calibration rig at 20 °C in advance. This constant was updated for the current investigations based on the calibration results performed at PTB. The offset Q_0 was included since the UFM showed clear flow velocity dependence. The result of the undisturbed case is shown in figure 1, there the systematic effects have been taken into accountant by the correction function. The deviation varies about ±0.05 % for all Reynolds numbers. Figure 2 presents the measurements for the disturbed case. As seen in figure 2 the linearity was only slightly affected but the disturber gave rise to an additional offset of about 1.25 %.

Orifice plate flow meter

The orifice plate flow meter is a differential pressure device. The measuring principle can be derived from the continuity equation and Bernoulli's equation. The measuring equation is given in equation 2.

$$q_m = \frac{\pi}{4} \cdot \frac{C_d}{\sqrt{1-\beta^4}} \cdot d^2 \cdot \sqrt{2\Delta p \cdot \rho} \qquad (2)$$

Where β=d/D, *d* is the orifice diameter, D is pipe diameter, Δp is the differential pressure and ρ is the density. The diameter ration β=0.5 % based on previous results [3].

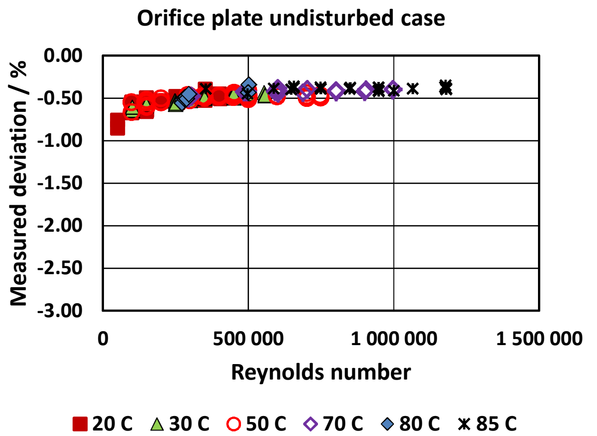

Figure 3. Results of undisturbed measurements: Measurement deviation of the orifice plate in dependence of Reynolds number at different temperatures.

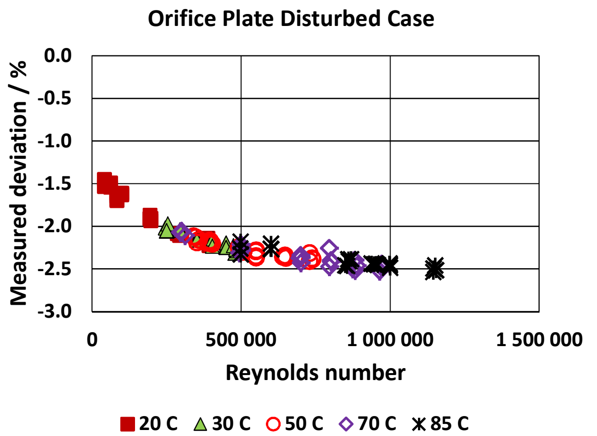

Figure 4. Results of disturbed measurements: Measurement deviation of the orifice plate in dependence of Reynolds number at different temperatures.

The measured deviation for the undisturbed case between the measured discharge coefficient (C_d) and the theoretical Reader-Harris and Gallagher (RHG) equation given in the standard [4] is presented in figure 3. As can be seen in figure 3 for a Reynolds number higher than around $5{*}10^5$ the measured values are within the specified uncertainty of 0.5 % for 0.2 ≤ β ≤ 0.5 [4]. The presented results in figure 3 follows the trend of the RHG for higher Reynolds number, with an offset of around -0.35 %. The disturbed results for the orifice plate are presented in figure 4. As can be seen the result shows a negative offset which is expected for this type of disturbance [3].

Venturi tube flow meter

The Venturi tube flow meter has the same measuring equation as the orifice plate. The Venturi tube is less sensitive to installation effects and upstream disturbance compared to the orifice plate. The measured deviation compared to the standard [5] is presented in figure 5. The measured discharge coefficient has a higher value than the standard but the results are satisfactory.

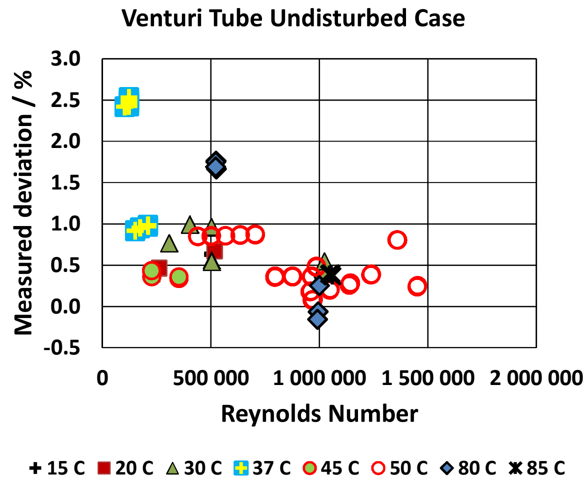

Figure 5. Results of undisturbed measurements: Measurement deviation of the Venturi in dependence of Reynolds number at different temperatures.

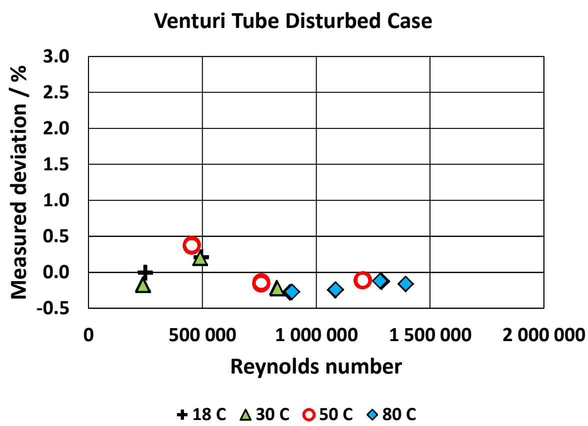

Figure 6. Results of disturbed measurements: Measurement deviation of the Venturi tube in dependence of Reynolds number at different temperatures.

The results from the disturbed measurements are presented in figure 6. As seen in figure 6 there is only a small offset in comparison with the undisturbed measurement which indicates that the Venturi tube is not very sensitive to this kind of disturbance. The deviation is smaller for the disturbed measurement and this might be due to that the flow disturber causes a more systematic flow distribution that in the undisturbed case. From the LDV measurements [1] it is shown that unsystematic flow distributions were found in the undisturbed measurements. The extrapolation function to higher Reynolds number was represented by:

$$C_d = 1.0016 + 2.940 * 10^{-9}Re$$

Electromagnetic flow meter

The measuring principle of the electromagnetic flow meter is based on measuring the generated electrical voltage, *U*, of the fluid passing by a magnetic field. The measuring equation is given in equation (3):

$$q_v = \frac{\pi \cdot D}{4 \cdot k \cdot B} \cdot U \qquad (3)$$

The EMF has a built-in temperature correction function of the diameter D. The results from the undisturbed measurements are shown in figure 7. As seen in figure 7 all the results are within ±0.5 %.

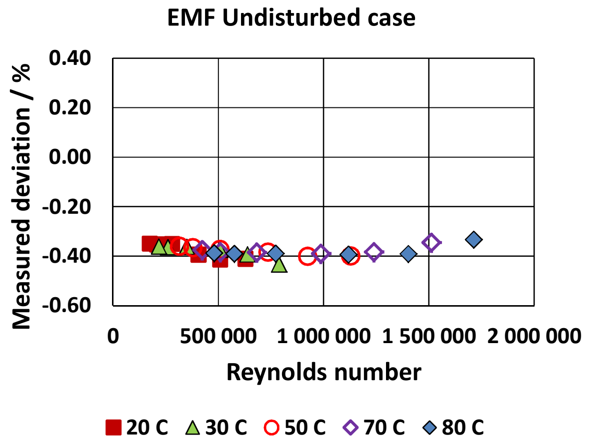

Figure 7. Results of undisturbed measurements: Measurement deviation of the EMF in dependence of Reynolds number at different temperatures.

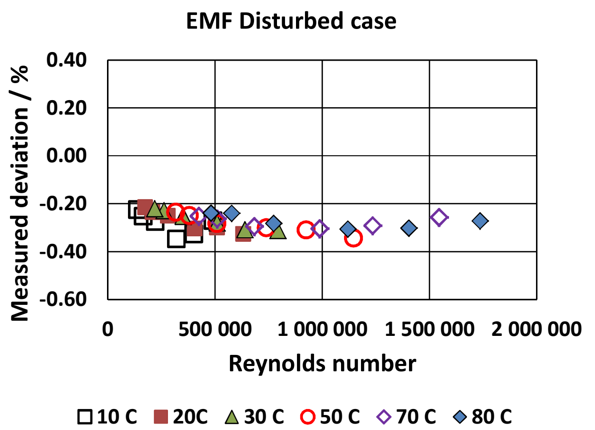

Figure 8. Results of disturbed measurements: Measurement deviation of the EMF in dependence of Reynolds number at different temperatures.

The measurements with the flow disturber are presented in figure 8. The disturbed measurement results only show a small offset of about 0.1 % in comparison with the undisturbed measurements. The conclusion for the EMF is that the internal reduction of this flow meter reduces the effect of this kind of flow disturbance effectively.

Summary

Four flow meters (electromagnetic, Venturi tube, orifice plate and ultrasonic flow meter) based on different measurement principles were investigated to establish an extrapolation model up above 200 °C. Both the EMF and UFM had temperature correction functions built-in and these correction functions seem to work efficiently. For the Venturi tube a temperature extrapolation function was found and for the orifice plate flow meter the measured discharge coefficient followed the theoretical RHG equation for high Reynolds numbers with an additional offset of about -0.35 %. The flow disturber only showed smaller effects on the EFM and the Venturi tube. The orifice plate on the other hand showed a considerable dependence on the flow disturber. However, this dependence was in agreement with earlier results. For the UFM an additional offset was observed in the measured deviation in comparison with the undisturbed measurements. This offset might be included in the temperature correction by another suitable choice of k_m.

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References

[1] O. Büker, P. Klason, P. Milota, K. Tawackolian, J. Frederiksen and A. K. Niemann, ”Investigations on flow meters used for accurate feed water flow measurement”, In manuscript, 2013.

[2] ISO 5167 . Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full - Part 1: General principles and requirements. 2003.

[3] O. Büker, P. Lau and K. Tawackolian, “Reynolds number dependence of an orifice plate”. Flow Measurement and Instrumentation, vol 30, pp 123 –32, 2013.

[4] ISO 5167. Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full - Part 2: Orifice plates. 2003.

[5] ISO 5167. Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full - Part 4: Venturi tubes. 2003.