Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 00 (2018) 000–000

Energy Procedia

www.elsevier.com/locate/procedia

16th International Symposium on District Heating and Cooling, DHC2018, 9–12 September 2018, Hamburg, Germany

Improving operational efficiency of power plants through on-site calibration of flow sensors

Ulrich Müller[1]*, Michael Dues[2], Waldemar Hübert[1], Christoph Rautenberg[1]

[1]*OPTOLUTION Messtechnik GmbH, Gewerbestr. 18, Lörrach, 79539, Germany*
[2]*ILA R&D GmbH, Karl-Heinz-Beckurts-Straße 13, Jülich, 52428, Germany*

Abstract

Growing industrial and legal need for precise heat and flow measurements in district heating facilities pushed the development and application of a technology for laser based on-site calibrations of large flow sensors. This calibration method works with direct flow velocity measurements along the pipe diameter through a custom made ball valve which is mountable during plant operations.

To accredit this calibration method an extensive uncertainty budget was created. The largest contribution to the uncertainty budget, the flow distribution in the relevant cross section of the pipe, was researched and quantified in an extensive project. The result of this project is a profile class model, where the resulting uncertainty of the measurement can be derived directly from the measurement itself.

The on-site calibration method is already deployed and executed in over 120 cases with a great variety in resulting flow sensor accuracies in within their operational conditions.

Keywords: flow measurement, innovative calibration technology, on-site calibration of flow sensors, flow sensor precision

* Corresponding author. Tel.: +49-7621-160-1515; fax: +49-7621-160-1526.
E-mail address: mueller@optolution.com

1. Motivation

A lot of operations and efficiency calculations for thermal power plants and district heating and cooling systems are based on measurements of large flow sensors (in this context greater than DN 150) and therefore, are strongly dependent on precise volume flow measuring data. These flow sensors (FS) are often used continuously for decades after an initial calibration at external test rigs under optimized conditions. An accredited recalibration of these FS within their actual operating conditions was not possible so far.

In the best case scenario those FS are unmounted and recalibrated on external test rigs. A large drawback of this procedure is the interruption of supply in addition to its already high costs. Furthermore, calibration conditions on test rigs can differ greatly from the actual operating conditions. These deviations are, for example

- Differences of the fluid parameters on test benches compared to supply systems, so e. g. large FS are calibrated on test benches with low temperature fluids and pressures
- Deviations from the well-known symmetrical flow conditions on test benches to the flow conditions in mounted state
- Long-term drifts, for example through abrasions (especially on orifices) and deposits and
- Deficiencies of the installation conditions (e. g. regarding the undisturbed lead-in length and/or grounding) of the FS.

So even if calibrated, the measurement uncertainty of the FS in operation remains fairly unknown.

More precisely measured values of FS may uncover hidden saving potentials and allow for more precise performance indicators, improving energy efficiency as well as day-to-day operations. A wide range of quality management objectives of district heating and cooling suppliers, namely higher accuracy of flow sensors for billing purposes, increased balancing certainty of energy flows and a verifiable quality of main benchmarks (e. g. primary energy factor, CO2 balance, CHP ratio etc.), could be supported by more precise measurements of volume flow rates.

These reasons pushed the development of a technology for the on-site calibration of large FS independent of their measuring principle in the mounted state, without the need to interrupt supply and under its actual operating conditions.

2. Description of the technology

The on-site calibration (OSC) method is based on the optical measurement principle of Laser Doppler Velocimetry (LDV). Using this measurement technology, local flow velocities are measured across one or multiple paths along the pipe diameter. Applying a rotational integration to the measured velocity profile(s) a volume flow can be calculated to calibrate the FS.

The essential optical access to the flowing fluid is realized by welding a specially designed ball valve and subsequent hot-tapping without the need to interrupt fluid flow, which is an operational advantage compared to recalibration on external test rigs. Using a sleeve inset a special designed window is positioned and aligned to the interior surface of the pipe to ensure that the flow remains unaffected by the optical access [1], see also Figure 1a. The safety of this process is reviewed and certified by TÜV Rheinland, which guarantees that the optical access can be created within systems of up to PN40.

Further preparations for the OSC involve mounting of the pressure window flange with subsequent installation of the measurement equipment itself, which includes the laser probe on a traversing system. The velocity profile of the fluid flow is scanned through automated movements of the LDV probe along a fixed axis parallel to the pipe diameter, as seen in Figure 1b. During this velocity scan, the measurement values of the FS under test are logged with the highest possible temporal resolution.

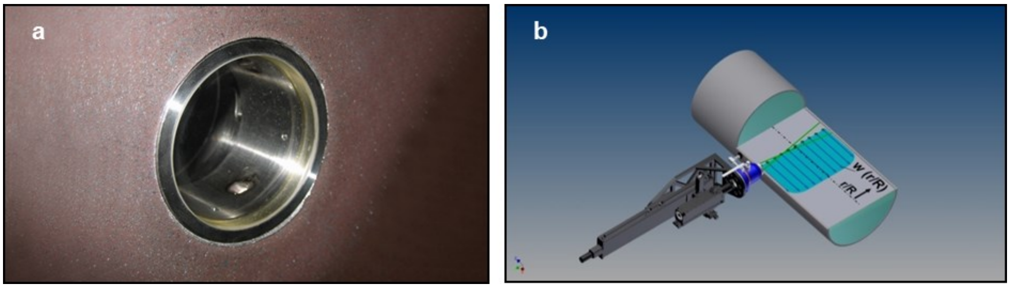

Figure 1: (a) Interior surface of the pipe with the inserted special window; (b) Demonstration of profile velocity (w(r/R)) measurement with LDV

To take the fluctuations of the volume flow rate during the measurement process into account the measured local velocity values are normalized with data of an additionally mounted ultrasonic clamp-on meter. This approach ensures the independence of the calibration from the FS under test, as neither linear error curves of the FS nor its correct temporal behavior can be guaranteed during the calibration. This case is especially relevant in calibrations during day-to-day operations, where the volume flow rate is fluctuating.

The normalization method is independent from the uncertainty and only reliant on the linearity characteristic of the device [2]. Therefore the used ultrasonic-clamp-on FS is special examined for this task. The measurement error of the FS is calculated through a comparison between the calculated LDV volume flow and a time averaged volume flow of the FS. The calibration procedure is repeated for different volume flow rates.

3. Measurement Uncertainties and Accreditation

Growing demand of the supply industry for reliable measurement values reinforced the need for a metrological accreditation of the OSC method. To achieve the credibility and traceability necessary for the demands of an accreditation according to the international standard ISO/IEC 17025 [3] a wide range of uncertainties from multiple sources needed to be quantified and put together in an extensive uncertainty budget as seen in Figure 2.

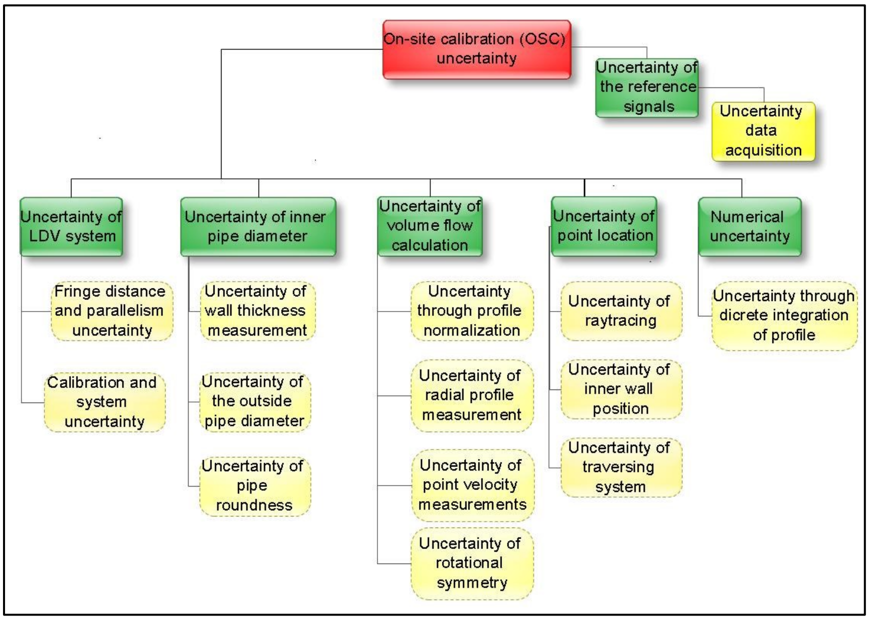

Figure 2: Overview about the different measurement uncertainties of the OSC method

Most of the contributing uncertainties to this method are derived fairly straight forward by using parameter studies with the measured profile or combined measurement uncertainty contributions of all involved tools within the calibration procedure. For example the tools for measuring the pipe geometry within the plane of calibration and the LDV-system. Other uncertainty sources such as the contributing uncertainty of each measured velocity point are modelled through the use of measurement specific Monte-Carlo simulations as those uncertainties invoke a slightly non-linear behavior and Monte-Carlo is a fitting tool to quantify the effects.

As the OSC method is a velocity path measurement the largest contributing point to an uncertainty budget is the actual flow velocity distribution within the cross section of the pipe at the optical access. To derive quantifiable estimations of the influences of unknown flow distributions to the calculated volume flow rates a research project, sponsored by the German Federal Ministry of Economic Affairs and Energy, was undertaken [4]. During this project a multitude of flow simulations and highly precise LDV flow measurements were used to develop a practicable and reliable model to describe the flow conditions and estimate its consequential measurement bias and uncertainty contribution to the OSC method.

The model is solely based on the velocity profile information one can derive from a path measurement and therefore requires no additional information outside the scope of the measurement. This model uses derivative and integral mathematical methods on the measured profile to classify it between five profile classes, each with their own measurement uncertainty and respective volume flow bias. Its underlying mathematical formulations are based on [5, 6] with further adaptions in order to have stronger distinctive capabilities for practical application in most diverse flow scenarios. The equations to these key coefficients are shown in (Eq.1 to 4).

Profile coefficient:

$$K_P = \frac{\int_{-0.6}^{0.6} \left| w(r) - w_{G\&H.Q}(r) \right| \cdot d\left(\frac{r}{R}\right)}{\int_{-0.6}^{0.6} w_{G\&H.Q}(r) \cdot d\left(\frac{r}{R}\right)} \quad \text{in \%} \tag{1}$$

with	r	coordinate of the pipe radius
	R	pipe radius
	w(r)	measured velocity profile along the pipe radius
	$w_{G\&H.Q}(r)$	fully turbulent velocity profile according to GERSTEN & Herwig [7] based on the calculated flow rate of w(r)

Asymmetric coefficient:

$$K_A = \frac{\int_{-0.6}^{0.6} \left(\frac{r}{R}\right) \cdot w(r) \cdot d\left(\frac{r}{R}\right)}{1.2 \cdot \int_{-0.6}^{0.6} w(r) \cdot d\left(\frac{r}{R}\right)} \quad \text{in \%} \tag{2}$$

Turbulence coefficient:

$$K_{Tu} = \frac{\frac{1}{0.4} \int_{-0.2}^{0.2} Tu(r) \cdot d\left(\frac{r}{R}\right)}{0.0853 \cdot \mathrm{Re}^{-0.0727}} \quad \text{in \%} \tag{3}$$

with	Tu(r)	measured turbulence degree along the pipe radius
	Re	REYNOLDS number

Level of profile overlap:

$$K_D = \frac{1+\left(\frac{r}{R}\right)_{\max}}{2} \qquad \text{in } \% \qquad (4)$$

with $\left(\frac{r}{R}\right)_{max}$ the maximum penetration depth of the profile.

This key coefficient model was validated with more than 200 external measured velocity profiles with known volume flow rates. In consequence more than 95 % of the calculated volume flow rates fulfilled the acceptance criteria of two times of the standard deviation.

Figure 3 shows examples of the different profile classes compared to a fully developed profile acc. to GERSTEN & HERWIG [7]. Even though those velocity profiles are largely different compared to a fully developed turbulent profile one can still classify them from metrological point of view and give a good estimation of the induced volume flow bias and uncertainty contribution to the OSC method.

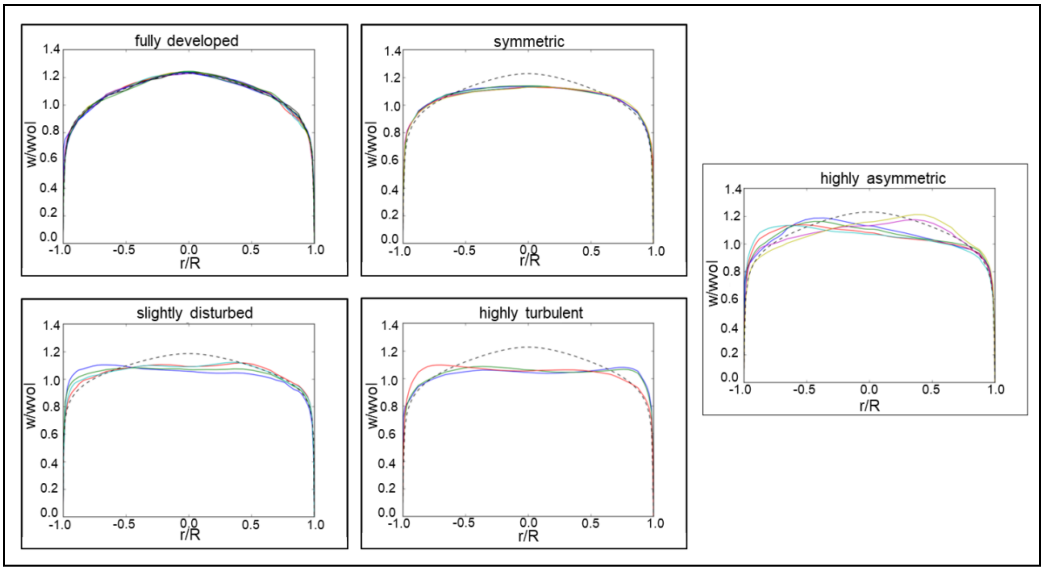

Figure 3: Examples of the different profile classes in contrast to a theoretical fully developed profile (GERSTEN & HERWIG)

In practice, the first three profile classes are most prominent for a carefully selected position of the optical access. The latter two profile classes appear mostly due to unexpected fluid distributions or due to restrictions in calibration positions inside power plants, forcing the OSC method to less favorable positions along the pipe system of the FS under test. As this classification method is based on the measurement itself, one cannot know beforehand how precise the measurement is going to be. Hence the position of the measuring path (the position of the welded ball valve) in regards to the flow situation is critical and must be chosen well.

The following Table 1 shows the achievable total measurement uncertainties for each one of these profile classes. The numbers are based on the measured value with a coverage factor of k = 2, expanding confidence interval to 95%. The minimum uncertainty for the profile class “fully developed” consists only the non-profile relevant contributions. For the combined uncertainties of all other profile classes the influence of the deviation from the rotation symmetry is the dominant contribution.

Table 1: Overview of the profile classes and their resulting measurement uncertainties

Profile class	Realistic measurement uncertainty (k = 2)
Profile class “fully developed”	0.7 %
Profile class “symmetric”	1.4 %
Profile class “slightly disturbed”	2.3 %
Profile class “highly turbulent”	2.7 %
Profile class “highly asymmetric”	4.2 %

In summary, it can be stated that the actual measurement uncertainty of the calibration strongly depends on the on-site flow conditions. On the basis of the on-site specific measurement uncertainty budget and metrologically traceable measurement tools, the calibration results are fully traceable to the national measurement standards of the German National Metrological Institute. This was one of the requirements for the accreditation as an on-site calibration laboratory according ISO/IEC 17025. The accreditation includes the following fluid conditions for the OSC method:

- Volume flow rate: 20 m^3/h to 30´000 m^3/h
- Fluid temperature: 5 °C to 150 °C
- Minimum bulk velocity: 0.3 m/s.

4. Benefits of the OSC technology and project examples

So far calibrations took place in a lot of power stations in Germany, Switzerland and Austria, with of a variety of motivations. The operating conditions of the measurements ranged from 50°C to 180°C of fluid temperatures, from 2 bars to 18 bar fluid pressure and pipes of sizes between DN 150 and DN 1000 (Figure 4a). There, the OSC measurements are useful auxiliary tools for heating grid planning and optimization processes, as well as input for FS lifetime logs for quality management purposes.

On another matter, OSC are often used as recalibration tool for flow sensors which were subsequently added as instrumentation to the grid lines. With those flow sensors often being ultra-sound clamp-on or other comparatively simple mountable instrumentation, they often lack the needed measurement precision. An additional calibration after mounting can decrease uncertainty of those flow sensors by a couple of percentages.

Another use of the OSC technology is the validation of FS precision in commercial practice between supplier and distributor of heat or water, where measurement errors have direct effects on accounting between the parties involved. E. g. one project covered calibrations of large water meters ranging from DN 500 up to DN 1200 within a large drinking water grid in Australia. An example of an OSC measurement situation on an underground water pipeline is given in Figure 4b. The distributor of the drinking water used the OSC method as there were found to be accounting discrepancies between the amount of water sold and the amount of water purchased, leading to accounting problems. The calibrations pointed out the flow sensors between supplier and distributor to be the dominating cause for the accounting mismatch.

Growing legal regulations and the increasing needs for more efficient and therefore more profitable operation lead to increasingly narrower design parameters of modern power plants. These design parameters and key factors range from thermic efficiency rates, CO2 monitoring, primary energy factors to cogeneration proportion. But calculation of these factors can only be as exact as the least precise data source that goes into these calculations. As such, flow rate instrumentation often proves to be the most uncertain part in the calculation chains. In actual operational conditions the measurement uncertainty of flow sensors is often larger than given by their calibration certificates.

Further issues with flow sensor precision often arise during a demerger of grid lines and sourcing power plants, where formerly just internal measurement points of heat and flow become relevant accounting points. These heat measurement points often were not initially designed to be precise measurement points but are suddenly subjected to be an important accounting measurement between two clients.

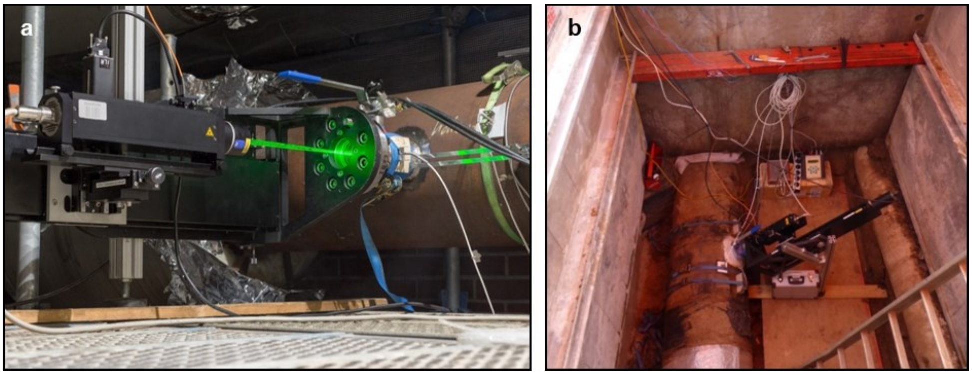

Figure 4: (a) OSC measurement equipment on a district heating pipe; (b) OSC measurement situation on an underground water pipeline

Generally speaking, the OSC technology is considered in cases where reliability and precision of FS is critical. It can support the calculation credibility of primary energy factors or CO2 balance calculations indirectly through improved flow sensor data. The OSC method also helps in process control and optimization, as improved and therefore more reliable flow sensor readings help identifying bottlenecks and grid reserves. Therefore, while not being a direct planning tool for new construction projects or district heating grids, OSC can assist as auxiliary tool for decision making in special cases.

Normally, FS of large diameters (larger DN 150) are not covered by obligatory calibration. Additionally, there exist no legal national regulations in many European countries for periodical recalibrations of flow sensors theses sizes in commercial practice. Thus the accuracy of FS remains entirely in the responsibility of the operators, where the large spectrum of operational conditions for FS often leads to inaccurate flow rate data.

Up to now, 123 large flow sensors were calibrated with the OSC method. The measurement errors of 25 flow sensors were greater than 4 % after subtraction of the inherent uncertainty of the OSC method. This means approximately 20 % of all inspected flow sensors show significant deviations from their initial test rig calibrations. The mean error of all tested flow sensors calculates to approximately -3.2 %. After subtracting the most typical uncertainty of the OSC method of 1.4 % (for profile class “symmetric”) a mean performance increase of 1.8 % is achieved. Transferred to accounting uncertainties in an exemplary case of a 50 MW measuring point at 150 heating days per year the OSC method would lead to a performance increase of 3´240 MWh per year. At an estimated price of 60 €/MWh the performance increase calculates to 194´400 €/year.

5. Summary

A new method to calibrate flow sensors under their operational conditions has been developed and already deployed in many different practical applications. Compared to other procedures of on-site checks of large flow meters within their operational conditions this method is directly traceable to national metrological standards, and therefore highly reliable in its measurement uncertainties and accreditable according to ISO/IEC 17025.

The nature of this laser optical calibration method is a direct fluid velocity profile measurement with the benefit of knowing the flow characteristics to a suitably sufficient degree to derive its own uncertainty budget. The installation of the necessary optical access requires no interruption of the supply. Depending on the flow conditions the combined uncertainty of this method ranges from 0.7 % up to 4.3 % in rare worst case practical scenarios. This method is highly suitable to improve flow sensor accuracy within cogeneration plants, district heating and cooling systems or also drinking water systems and thus very beneficial for optimization processes, calculations of performance indicators or accounting purposes. The OSC technology works seamlessly in conjunction of daily cogeneration plant operations as the calibration itself works within operation conditions and without the need to interrupt supply. The OSC method also has the added benefit that it automatically calibrates the flow sensor at test points of day to day operations, where accuracy matters the most.

Acknowledgement

We would like to thank the German Federal Ministry of Economic Affairs and Energy for its continued support within the EnEff:Wärme project "On-site calibration of large flow meters in district heating systems" and the involved partners, the German National Metrological Institute Physikalisch-Technische Bundesanstalt, the Technical University of Berlin and the three representatives of industry, VATTENFALL Europe Heat Berlin GmbH, ILA R&D GmbH and OPTOLUTION Messtechnik GmbH.

Abbreviations

FS	Flow sensor
LDV	Laser Doppler velocimetry
OSC	On-site calibration

References

[1] Dues, M.; Müller, U.; Kallweit, S., 2011. Method for measuring a flow, installation unit and measuring apparatus, Application: 30.11.2011. DE, *Patent Specification* EP 2 389 566 B1. 16.11.2016

[2] ISO/TC 30/SC 5, ISO 3966:2008. Measurements of fluid flow in closed conduits – Velocity area method using Pitot static tubes. ISO Standard, 2008.

[3] ISO/CASCO, DIN EN ISO/IEC 17025:2005. General requirements for the competence of testing and calibration laboratories. ISO Standard, 2005.

[4] AGFW – Der Energieeffizienzverband für Wärme, Kälte und KWK e.V.. "EnEff. Wärme – Energieeffizienz in der Fernwärme durch Vor-Ort-Kalibrierung von Durchflussmessgeräten – Kopplung von laseroptischen und numerischen Verfahren". Gemeinsamer Abschlussbericht der Partner ILA R&D GmbH, OPTOLUTION Messtechnik GmbH, Physikalische-Technische Bundesanstalt, Technische Universität Berlin, VATTENFALL Europe Wärme AG, *AGFW, Forschung und Entwicklung,* Heft 46, Frankfurt/Main, 2018.

[5] Yeh, T., T. und Mattingly, G., E. Pipeflow downstream of a reducer and its effects on flowmeters. J. *Flow Measurements and Instrumentation.* 5 (1994), S. 181-187.

[6] Russo, F. und Basse, N.T. 2016. Scaling of turbulence intensity for low-speed flow in smooth pipes. *Flow Measurements and Instrumentation.* 52 (2016) 101-114, 2016.

[7] Gersten, K. 2005. Fully developed turbulent pipe flow. In Merzkirch, W. (Ed.) *Fluid Mechanics of Flow Metering.* Berlin Heidelberg, New York: Springer-Verlag, 2005.