NEW ON-SITE CALIBRATION TECHNIQUE FOR LARGE FLOW METERS USING LASER DOPPLER VELOCIMETRY

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1 ABSTRACT

This paper presents a new method of calibrating flow meters of 100 to 1000 mm diameter whilst on-site and in operation using Laser Doppler Velocimetry (LDV). The technique has been tested and demonstrated in the laboratory and in the field. Primarily developed for calibrating district heating meters, the technique is also suitable for measuring flow in other clear fluids.

Calibration of installed large district heating meters using traditional methods is difficult, if not impossible. It is often a labour demanding, time consuming and costly task to remove and send a meter for off-site calibration. Using LDV for on-site calibration is an attractive alternative.

LDV is an established optical technique for measuring point velocity in clear gasses and fluids and is used in a wide range of R&D applications. Using LDV it is now possible to carry out accredited on-site calibration of large flow meters up to 1000 mm in diameter with water flow velocities from 0.01 to 6.0 m/s.

Using the LDV technique on-site measurements can be carried out with an uncertainty of ±0.9% depending on specific flow conditions and accuracy requirements. Calibration is based on a series of measurements taken over 2 to 4 pipe diameters. Optical access to the flowing fluid is obtained by installing specially designed windows close to the flow meter. Point velocity measurements are converted to volume flow rate by using known flow rate estimation techniques.

In addition to flow rate estimates the LDV technique can also be utilised to map flow conditions, such as the result of disturbances from pipe bends and valves etc. By rotating the LDV measurement instrument about its optical axis the tangential or swirl velocity component can be measured and the degree of swirl and flow disturbance can be mapped.

The technique and practical experience from measurements will be presented. Examples of laboratory and field measurements, including examples of flow profiles for non-disturbed and disturbed flow conditions will be given.

Keywords: On-site calibration, flow measurement, flow meters, district-heating meters, LDV, Laser Doppler Velocimetry, flow disturbances, flow conditions.

2 INTRODUCTION

In district heating supply networks it is a typical problem that large flow meters are difficult, and sometimes impossible, to calibrate once they have been installed and are in operation. However, accurate measurements from large district heating meters are important and regular meter calibration is the best way of obtaining information about the meters' current measurement ability.

In Denmark alone there are approximately 1000 large meters in the district heating system, and the majority of the heat produced and sold is billed according to these meters. With an annual Danish district heating production of about 90 PJ, metering errors are an important factor with regard to fair billing between the district heat supplier and the district heating companies. In addition to using meter readings for billing purposes, district heating suppliers are interested in

using data from the meters to plan heat production relative to a forecasted demand. Any difference between the measured and the true flow values can easily lead to excessive primary energy consumption. Likewise, inaccurate or unreliable measurements can result in incorrect judgement of the efficiency of a heat production plant and of the heat losses in the distribution pipe network.

Although on-site meter calibration is attractive, earlier methods have not demonstrated adequate accuracy for district heating measurement. An alternative to these techniques is a new application of a well-known optical measurement technique called Laser Doppler Velocimetry (LDV). LDV has origins in measuring flow velocity in air and gasses but more recently LDV has been applied to measuring the velocity of flowing water - including district heating water.

In brief, LDV can be described as a non-contact optical measurement technique for measuring local flow velocity. Measurements do not disturb the flow as the LDV principle allows measurements to be made without inserting a physical object into the flow. Transparent windows allow optical access to the flowing medium. The operating principle involves focusing two laser beams at the point where velocity is to be measured and then sensing with a photodetector the light scattered by tiny particles carried along with the medium as they pass through the laser focal point. LDV measures point velocity and these values have to be converted to a flow rate to make it comparable with the readings from a flow meter. By taking measurements at several points across the diameter of a pipe a flow profile can be constructed and the flow rate can be calculated by processing the data making up one or more flow profiles.

Detailed laboratory measurements using LDV have been carried out at the Danish Primary Flow Laboratory located at the Danish Technological Institute in Aarhus, Denmark. Different flow conditions, including non-disturbed and disturbed flow have been investigated. The laboratory has also carried out laboratory measurements in co-operation with the Fluid Mechanics Laboratory at the Department of Mechanical Engineering at the Technical University of Denmark and with Danfoss (now Siemens Flow Division) at their facilities in Nordborg, Denmark.

On-site LDV measurements have been carried out on meters of 350, 500 and 1000 mm diameter. Optical access has been obtained through glass windows built into a specially constructed pipe section installed in the district heating installation in close proximity to the flow meter.

The Danish Technological Institute is accredited by DANAK (Danish Accreditation) to carry out on-site calibration of flow meters with diameters between 100 mm and 1000 mm and flow velocities from 0.01 to 6.0 m/s. Measurements can be carried out with an uncertainty of ±0.9% depending on specific flow conditions and accuracy requirements. In addition to accredited calibrations, LDV measurements can be carried out in pipes and in and around components such as pumps or valves to investigate flow conditions and illustrate and document the effects of flow disturbances.

3   TRADITIONAL CALIBRATION OF LARGE DISTRICT HEATING METERS

3.1   Removal and calibration of large district heating meters

Once a large district heating meter is installed and in operation it is often a difficult task to carry out regular calibration of the meter as calibration inevitably involves removing the meter in order to send it to a suitable calibration facility. Some meters are impossible to remove from the installation because they are welded into the piping system. Where meters can be removed, post-installation alterations made to the installation close to the meter can result in poor access conditions or reduce access to an extent where this becomes impossible. Large meters can be relatively cumbersome and often are installed in difficult to reach locations - high up or against a wall – or in the corner between a wall and the floor or the ceiling. Usually the meters are so heavy that it is necessary to use either a crane or winch system to remove and re-install them.

There are a limited number of facilities in Europe capable of calibrating meters larger than 200 mm in diameter or with a flow in excess of 400 – 500 m³/h, so calibrating large meters can be a costly and time consuming operation.   Just about all the large calibration facilities operate with cold water only, i.e. at temperatures of approximately 20°C, whereas the temperature required for legal calibration of a district heating meter requires 50°C or more.   Off-site calibration takes place in calibration rig set-ups with favourable flow conditions, which do not take account for actual installation situations.   Removing a meter for calibration also involves the installation of a replacement meter, which can take the place of the normal meter while it is being calibrated.

3.2   Existing on-site calibration methods

Previous work [1, 2] has addressed the use of mobile methods for calibrating large flow meters on-site.   [1] concludes that the most relevant methods were either the use of radioactive trace particles or the comparison with clamp-on meters using an ultrasonic measurement principle. The report also concludes that documentation for the accuracy of the two methods was, at that time, not sufficient to meet the requirements demanded for district heating measurements.

The use of radioactive trace particles is investigated in [2]. In particular two methods – the transit time method and the dilution method - were studied. The principle of the transit time method is based on injecting radioactive trace particles into the pipe containing the flowing fluid. Downstream of the injection point two detectors placed at a known distance apart detect the passing of the trace. The method requires accurate information about the volume in the length of pipe between the two detectors and injection and detection must take place in a suitably long and straight length of pipe. In addition, the location of the injector and the detector must be chosen with considerable care to avoid that the bursts of trace particles developing long "tails" which can give rise to increased uncertainty and error.

The principle of the dilution method is based on continually dosing a steady stream of trace material into the main piping system via a smaller pipe and the concentration of trace material is measured downstream of the point of injection. The method requires the means of extracting a small stream of fluid from the main stream, which is then used as a measurement sample. A successful measurement demands careful apparatus construction and good physical conditions. The method seemed best suited for use as a supplement to other calibration methods.

Measurements using clamp-on ultrasonic meters involve attaching an ultrasonic transmitter and a receiver to the uninsulated surface of the pipe in question. The measurement principle is identical to the principle used by intrusive ultrasonic meters, i.e. the speed of the water in the pipe is found by measuring the difference in the time taken for two beams of acoustic waves to travel the distance between transmitter and receiver. The method requires accurate measurements of the pipe's outer diameter, pipe wall thickness and information about the extent of fouling or other material deposits that may be present on the inside surface of the pipe. Other practical problems include clamp slippage causing changes in acoustic beam path and temperature expansion. A common problem with clamp on meters is sensitivity to flow velocity profile – ultrasonic meters will give different readings for axisymmetric profiles of different shape but identical average velocity. It is estimated that the total system inaccuracy is still unsatisfactory for on-site calibration of large district heating meters.

3.3   LDV – a new tool for accredited on-site calibration

An attractive alternative measurement method is LDV.   LDV is one of a number of optical techniques that can be used to measure and map fluid flow conditions. Optical techniques involve taking measurements of the speed of small particles in the fluid and LDV is considered to be one of the more well-established of these techniques. The use of LDV has earlier been restricted to the laboratory, but recent developments within the field of fibre optics and electronics have resulted in compact, robust and mobile LDV equipment.   This has allowed LDV to move out of the laboratory and into the field, with LDV becoming a relevant measurement technology for on-site calibration of district heating flow meters.

The potential of using LDV in district heating applications has been addressed by earlier research work, mostly carried out in Germany. At the Physikalisch Technishe Bundesanstalt (PTB) in Berlin LDV has been used in hot water flow environments [3]. LDV, together with a flow meter transfer standard, has been used to calibrate a turbine flow meter as a secondary standard for a hot water test rig operating at temperatures between 20°C and 180°C and at flow rates between 50 and 120 m^3/h. LDV measurements on a district heating application have been carried out at Ph.D. level at the Technical University of Berlin [4] and [5]. LDV measurements were taken on practical district heating installations where calibrated flow meters had been used, but where the operational conditions could be very different to conditions during initial calibration of the meters on calibration rigs, i.e. distorted flow profiles due to disturbances in the pipe system. Different sources of uncertainty involved with measuring local fluid velocity and flow rate were investigated and measurements included a series of tests on a district heating substation. Results led to an analytic model for calculation of uncertainty.

Work carried out by the Danish Technological Institute in co-operation with Danish district heating companies and supply companies, meter manufacturers, an LDV manufacturer and the Technical University of Denmark [6] has shown that LDV can be used for on-site testing and calibration of large district heating meters. Considerable laboratory and field work has demonstrated that measurement uncertainties of maximum 0.9% can be obtained from regular flow conditions. In 2001 the Danish Technological Institute receiving accreditation from DANAK (Danish Accreditation) to carry out laboratory point-velocity calibrations with LDV in flows up to 6.0 m/s. In 2003, the scope of the accreditation was expanded to include on-site calibration of flow meters with diameters up to 500 mm, and with flow disturbances (swirl) less than 10%. In April 2005 the accreditation was extended further to include on-site calibration of flow meters with diameters up to 1000 mm, and flow disturbances (swirl) less than 20%.

LDV is a versatile tool and can also be used for other flow related applications. These include improved understanding of flow disturbances arising from various installation effects either from the lay-out of the installation itself (single elbows, double elbows, double elbows out-of-plane etc.) or from specific components in the installation such as valves and pumps.

4   A BRIEF DESCRIPTION OF LASER DOPPLER VELOCIMETRY

4.1   Historical overview

LDV originated from work at Columbia University, USA by Yeh and Cummins in the early 1960's and the first successful measurement of local fluid velocity by the laser Doppler method was reported by these authors in 1964 [7].

In the late 1960's, frequency trackers capable of providing time resolved velocity information appeared. However their use was limited and in the 1970's counter processors were developed as an alternative to frequency trackers. Counters measure the time-of-flight of a particle through a known number of interference fringes in the measurement volume. They became popular for measurements in air, and for back-scatter set-ups with non-continuous signals. Counters work best with good signal-to-noise ratios, which unfortunately are not always available.

In the early 1980's, burst correlators and burst spectrum analysers became commercially available. These are very robust even when dealing with noisy signals, and gave the benefit of better data quality especially in back-scatter set-ups. Thus the use of smaller lasers for back-scatter became a feasible option. In the mid-1980's, optical fibres had been developed to such a degree that they could be used to transport high-power laser light and maintain good beam quality at the output. This was a revolution for LDV optics, because the bulky laser source could now be separated from the LDV sensor arrangement or "probe", which became compact and easy to traverse. Turn-key optical systems became commercially available from 1992.

4.2 Using LDV to measure water flow

LDV is the point measurement of velocity by means of laser light and it is based on the Doppler effect. A simple illustration of the LDV measurement principle is shown in figure 1.

A laser beam is split into two beams, which subsequently converge again at the measurement point. Light is reflected when the laser beams illuminate a tiny particle moving with the fluid and passing through the measurement volume. The speed of the particle causes a Doppler shift of the reflected light's frequency and produces a photodetector signal directly related to velocity. The illustration shows the back-scatter principle for measuring the fluid velocity. Back-scatter only requires optical access from one side of the flow, which makes access and traversing easier.

Fig. 1 - Simple illustration of the Laser Doppler Velocimetry (LDV) principle

LDV measurements require optical access to the fluid, e.g. a window, so that the incoming laser beams are able to penetrate the medium and for the back-scattered light reflected from moving particles to be received on the photo detector. Ideally the measurements are carried out on a steady flow and through a number of quickly repeated measurements that are treated statistically in order to obtain a representative mean velocity. The LDV measurement principle assumes firstly that particles exist in the medium, secondly that the particles move with the same speed as the fluid and thirdly that the particles are able to reflect light from the laser beam.

LDV systems can be based on various different laser types. The work presented here is based on measurements taken with a 10 mW Helium-Neon (He-Ne) laser and this relatively low-power laser has proved adequate for measurements on district heating water. Normal district heating water has sufficient clarity and there are enough natural particles of the correct size.

Recent developments in LDV signal processing systems have been significant. Sophisticated burst correlators and burst spectrum analysers are now commercially available and utilise the full signal information to determine the Doppler frequency. The equipment is robust even when dealing with noisy signals giving the benefit of better data quality especially in back-scatter set-ups. A Burst Spectrum Analyser (BSA) has been used for spectrum analysis of the Doppler signals

5 ACCREDITED ON-SITE CALIBRATION OF FLOW METERS USING LDV

5.1 Flow rate estimation techniques

Measurements with LDV are point measurements. In order to evaluate the flow rate in a pipe accurately, many point measurements have to be integrated to obtain an estimate for the bulk mean velocity. Estimating flow rate from point measurements is a common problem addressed by several standards and papers, in particular ISO-3354, 1988 [8] and VDI-2640, 1993 [9]. In the method developed here the "constant area" method described in [8] and [9] has been used.

The cross sectional area of a pipe is divided into sub-areas with constant area and the centre of mass for each sub-area is used for the measurements. The mean velocity is then found as the numerical mean value of all measured mean velocities. A correction for the very steep velocity profiles found near the wall is used. Figure 2 illustrates the method.
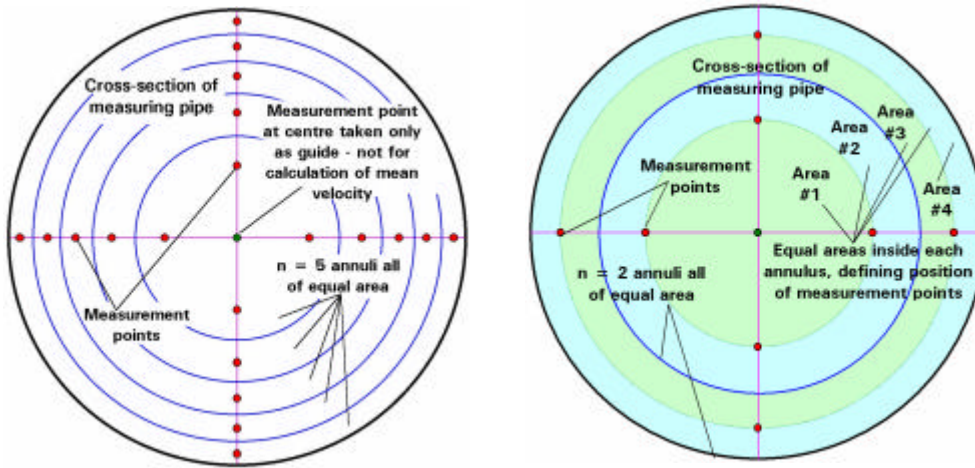

Fig. 2 - The constant area method. The figure on the left shows the model for 5 circles, where measurements over 4 radii are taken. The figure on the right shows the model for 2 circles and the positions of the measurement points.

5.2 Optical access and window constructions

Optical access is necessary to measure the velocity of the moving district heating water and special windows have been developed for this purpose. Laboratory and field installations operate under different temperature and pressure levels, which have resulted in different solutions for these applications. Figure 3 and 4 show window constructions for laboratory and field measurements respectively.

Fig. 3 - Window constructions for laboratory use

It is important to ensure that the glass windows are clean before carrying out measurements. Dirty windows can impair measurements, reduce data-rate and increase the time necessary for measurements. It is especially important to clean the inner side of the glass before installation of the window construction and over longer periods of time it would be an advantage to clean the inner side of the glass during routine shutdowns. However once the window construction is in place, the good quality and cleanliness of normal district heating water in the Danish district heating systems should not lead to problems with dirty windows.
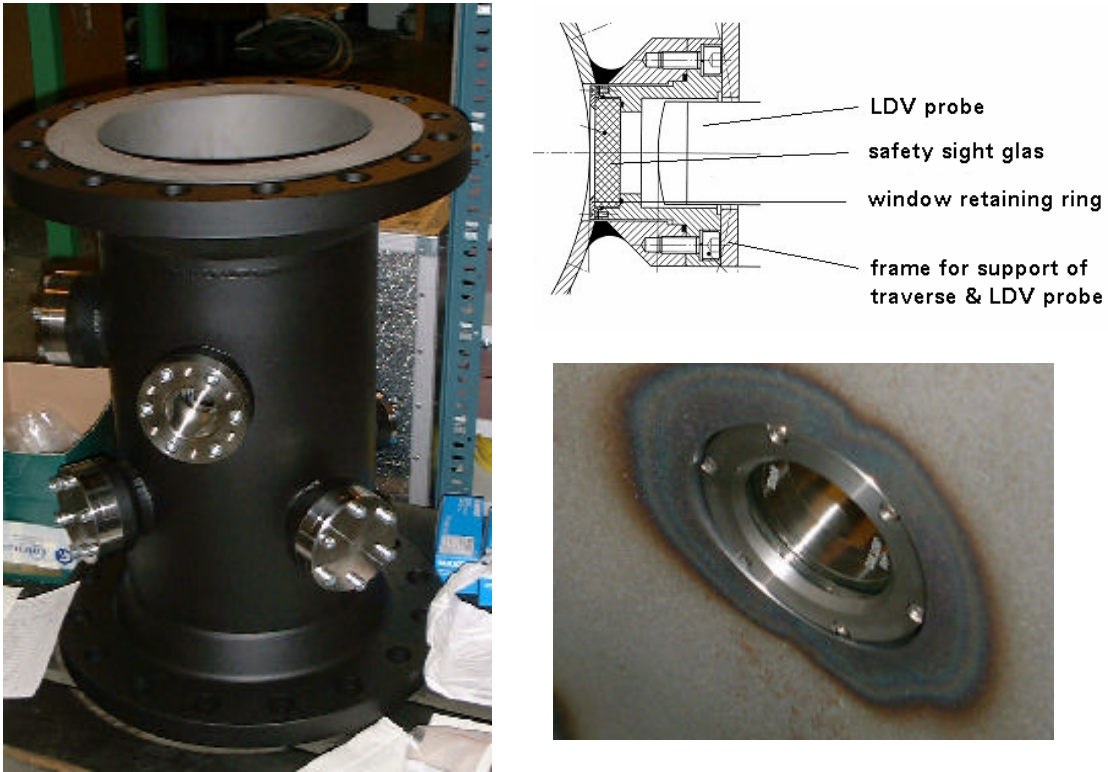
Fig. 4 - Window construction for field measurements, including detail of window inside the pipe

5.3   Measurement accuracy and uncertainty

Taking measurements with LDV equipment gives rise to various contributions to the overall uncertainty. Table 1 shows the different uncertainty contributions

Table 1 - Uncertainty contributions for LDV measurements

Type of uncertainty	Uncertainty contribution (relative %)
Calibration of LDV system and velocity change along measuring volume	0.03
Drift of LDV system	0.03
Refraction index of window and medium	0.06
Velocity variation particle/medium	0.03
Geometrical position of points	0.32
Method for velocity rate estimation and short time flow rate fluctuations	0.23
Cross sectional area	0.17
Long time flow rate fluctuations	0.04
Root mean square of uncertainties	0.44
Expanded uncertainty (k = 2)	**0.88**

5.4   Example of accredited on-site calibration – a 500 mm flow meter

The first accredited on-site LDV calibration was carried out on a 500 mm district heating flow meter at a flow rate of approximately 1300 m^3/h. Figure 5 shows an illustration of the installation set-up and a photograph of the actual installation.
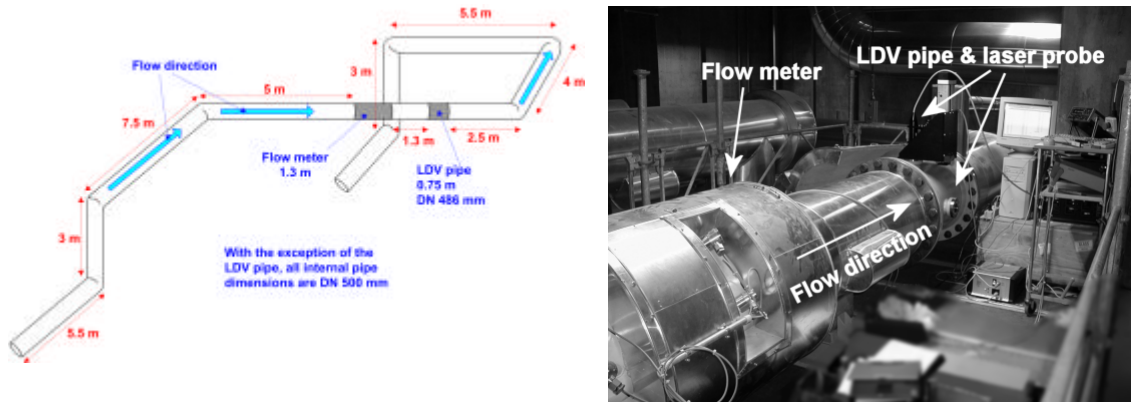

Fig. 5 - On-site LDV calibration of a 500 mm district heating flow meter

The result of the on-site calibration was a measured error of –0.55% with a total uncertainty of 1.64%. The relatively large uncertainty is due to measurements being taken over 2 diameters only, whereas 4 diameters would normally be specified. Flow profile plots have been drawn up for different angles and figure 6 shows two examples of these.
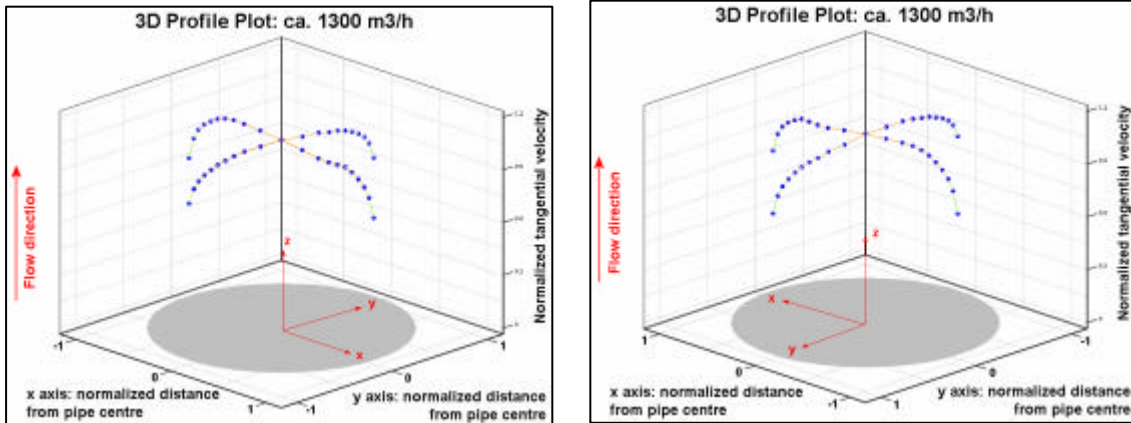

Fig. 6 - Examples of a flow profile plot with point-of-view rotated 180° during on-site calibration of a 500 mm diameter meter

5.5   Example of accredited on-site calibration – a 1000 mm flow meter

Another example of an accredited on-site LDV calibration of a large flow meter was carried out on a 1000 mm district flow meter at flow rates of approximately 400, 1500, 2900 and 4700 m^3/h.

Figure 7 shows an illustration of the installation set-up and a photo of the actual installation during measurements.
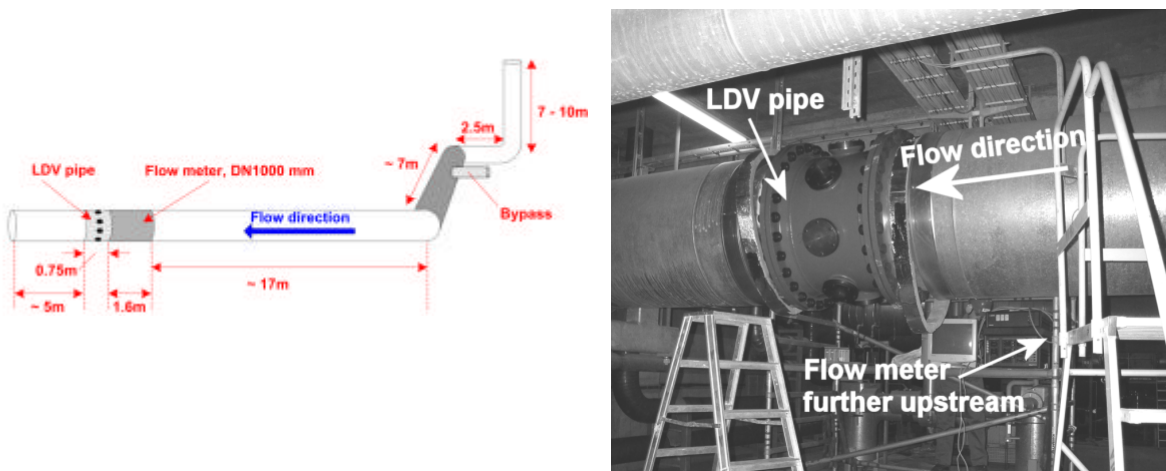
Fig. 7 – On-site LDV calibration of a 1000 mm district heating flow meter

The result of the calibration is shown in table 2.

Table 2 - Results of on-site LDV calibration of 1000 mm flow meter

Nominal flow (m³/h)	Relative error of customer meter compared with LDV measurements (%)	Uncertainty of error (%)
400	0.10	0.90
1500	0.80	0.90
2900	0.02	0.90
4700	0.83	0.90

For each flow rate, several 3D profile plots of the flow were compiled for different measurement angles. Furthermore, a contour-plot of the swirl (i.e. the ratio of the tangential velocity to the average axial velocity) was compiled. An example of both is shown in figure 8.
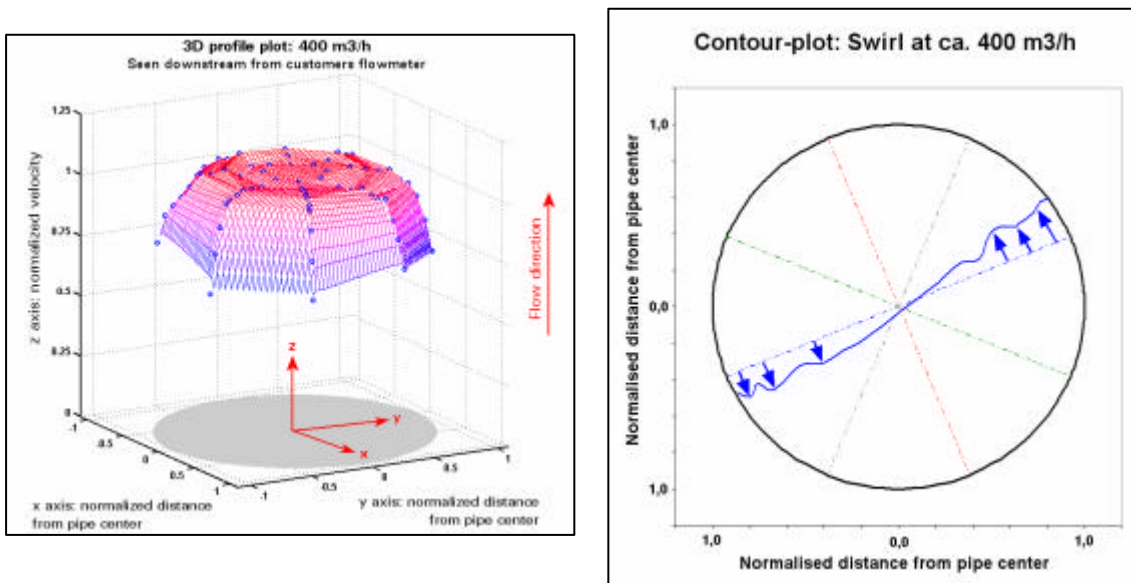

Fig. 8 - Flow profile plot for 400 m³/h (left). 3D profile and contour-plot of the swirl (right).

The contour-plot can be understood by visualizing the flow as projected out of the page. The dotted lines denote the axes measured across, while the blue line shows the tangential velocity at each point. The arrows show a swirl whereby the flow is rotating anticlockwise. In this example the maximum extent of swirl is approximately 10%.

6   GREATER UNDERSTANDING OF FLOW PROFILES AND DISTURBANCES

6.1   Disturbed flow profiles and swirl flow

Disturbed flow can result from any obstacle in the path of the flowing medium, e.g. various piping configurations such as bends, elbows, double pipe bends, semi-open valves, pumps etc. A set-up leading to one of the most disturbed types of flows consists of two 90° elbows in an "out-of-plane" configuration. After passing the first 90° bend the velocity profile is skewed. Passing another pipe bend turned 90° to the first bend results in a rotation of the flow. This type of flow is called swirl flow and is of interest in district heating systems as it can influence readings from ultrasonic flow meters. LDV can be used to measure swirl flow as by simply rotating the laser probe by 90° the velocity component perpendicular to the axial direction of the flow can be measured. By measuring across the pipe diameter the magnitude of the swirl flow can be mapped and calculated. The effects of swirl are interesting, especially the effects of swirl on the measurement of district heating water flows and the Flow laboratory at the Danish Technological Institute has carried out laboratory and field measurements on flows where swirl has been provoked.

6.2   Examples

A 3-D view of a non-disturbed flow profile is shown from two angles in figure 9.
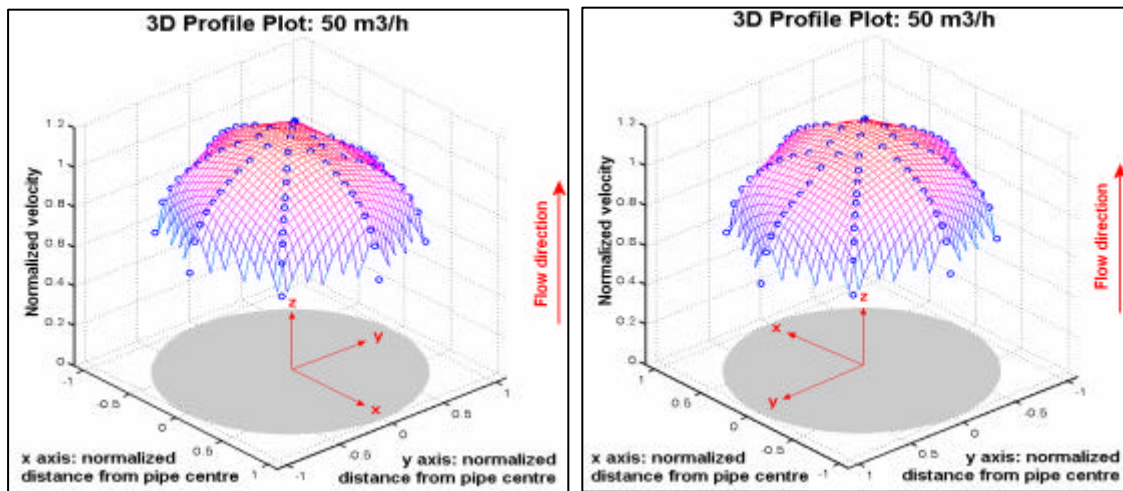

Fig. 9 - Two 3-D views of a non-disturbed flow profile with point-of-view rotated 180°

The measurements were taken using a laboratory set-up with the window construction shown in figure 3 and a flow of 50 m³/h. The result of the LDV measurements was an error of 0.03% and an uncertainty of 0.74%

For detailed laboratory investigations a 150 mm diameter swirl generator has been constructed and laboratory measurements have been carried out. Figure 8 shows the 150 mm inside diameter swirl generator used by the Flow Laboratory at the Danish Technological Institute and a 3-D view of the disturbed flow profile resulting from this.
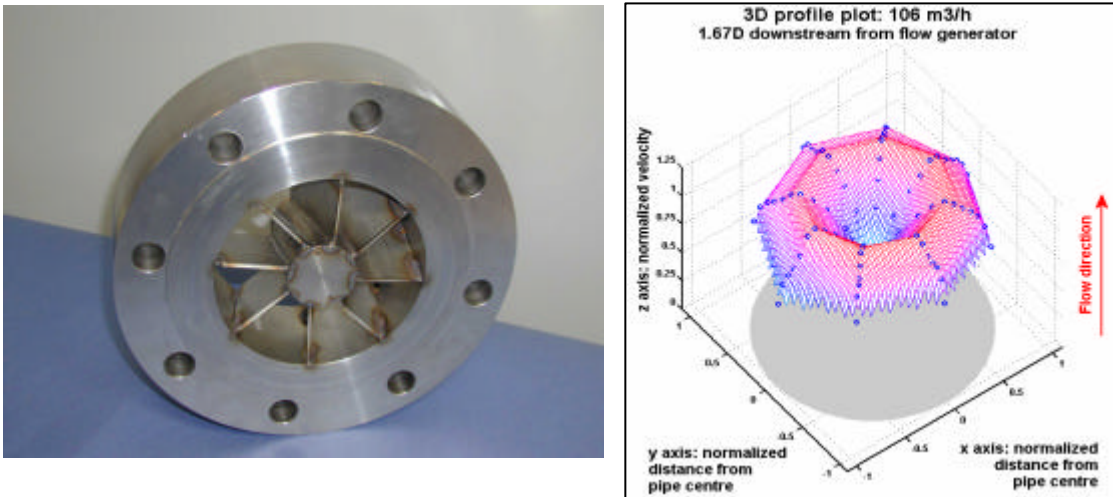
Fig. 10 - Swirl generator and the disturbed flow profile resulting from the swirl generator

Figure 11 shows another 3-D view of the disturbed flow profile 1.7D after the disturbance and a plot of the measured tangential component of the flow after the swirl generator (swirl).
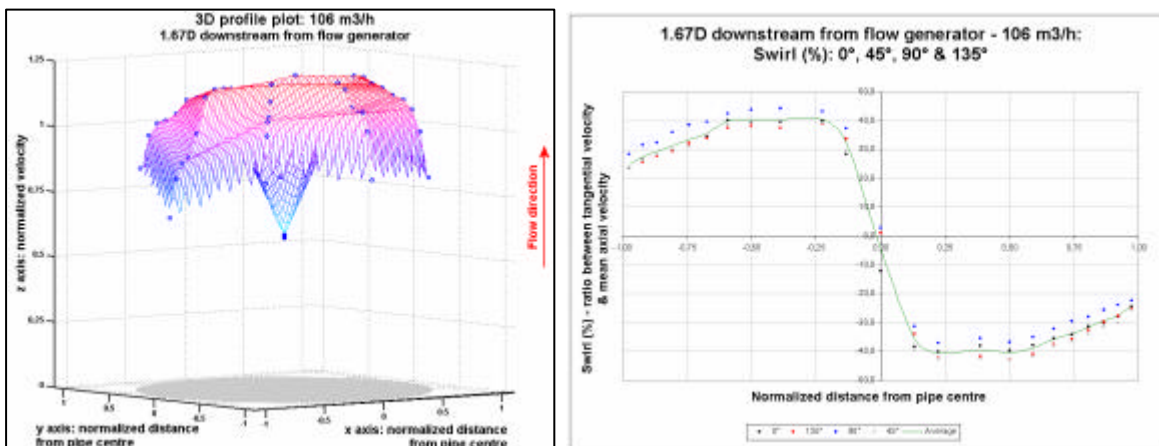

Fig. 11 - Disturbed flow profile after swirl generator and amount of swirl

Experience with these laboratory measurements will be valuable when evaluating flow profiles from measurements in the field.

7   CONCLUSIONS

An optical measurement technique based on Laser Doppler Velocimetry (LDV) has been developed to enable on-site calibration of large flow meters in operation. The method has been tested in the laboratory and demonstrated in the field on large district heating meters.

An accredited service covering LDV measurements and subsequent data processing is now available for flow meters of 100 to 1000 mm in diameter and water flow rates of 0.01 to 6.0 m/s. Depending on specific local flow conditions the field measurements can be carried out with an uncertainty of ± 0.9%. Accredited calibrations have been carried out on 500 mm and 1000 mm diameter flow meters.

In addition to flow rate estimates the LDV technique can be used to map flow conditions, for example the result of disturbances caused by pipe bends, combinations of pipe bends, pumps and valves etc. By rotating the LDV measurement instrument about the optical axis the tangential or swirl velocity component can be measured and the degree of swirl and flow disturbance can be mapped.

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