

# A NEW APPROACH TO IMPROVE REPRODUCIBILITY OF ULTRASONIC FLOW METERS USED IN FULLY DEVELOPED FLOWS

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## Abstract

Due to its high repeatability ultrasonic flow meters (UFM) are ideal instruments for interlaboratory comparisons. The present paper attempts to improve the performance of UFM for interlaboratory comparisons by estimating weighing factors that reduce the intrinsic errors of this technology. The results have been tested with a DN200 five parallel path time of flight (TOF) UFM at Bilateral comparison within the Physikalisch-Technische Bundesanstalt. Outstanding results have been accomplished.

## Introduction

Ultrasonic time of flight flow measurement devices (UFM) have proven their accuracy and quality in several application fields; its use as a transfer standard delivers very high repeatabilities in the order of 0,01% for example at the High Reynolds Number flow rate facility at the NMIJ [1].

For its Industrial application, besides mandatory design factors as safety, durability, energy consumption, size and weight, other important design optimization criteria is robustness against particular environments where the meters are installed. For example: fluid property variations, inclusion of air or other phases, path failures, clogging, asymmetric flow profiles, secondary velocity components are being considered and deeply studied. See for example [2].

This paper will consider the application of UFM in Interlaboratory comparisons at ideal and constant conditions. The success of such comparisons depends largely on the quality of the flow meters used. Repeatability and reproducibility must be in the order of 0.01%. UFM are predestinated to be used also in this application field.

In the first part of this paper, based on models of fully developed turbulent flow profiles, the sensitivity of the error curve to variations of the weighing factors is analyzed.

In the second part, by analyzing the effects occurring in nearly ideal conditions, it is shown that it is possible to find weighing factors with an excellent performance for applications like interlaboratory comparisons.

In a third part, the raw measurement data of a high end industrial TOF flow meter has been processed by using

the proposed method. The measurement campaigns have been performed at two different water flow test facilities of the Physikalisch- Technische Bundesanstalt (PTB).

Finally, the results are discussed, and further questions to be answered defined.

Several examples, calculations and measurements are based on an existing five parallel path time of flight flow meter in DN200. The path positions are fixed at 0R 0.5R and 0.8R; They are called P0, P50 and P80, and are installed at +45°, -45° and +45° respectively. Raw data without any compensation or correction functions has been used in all cases.

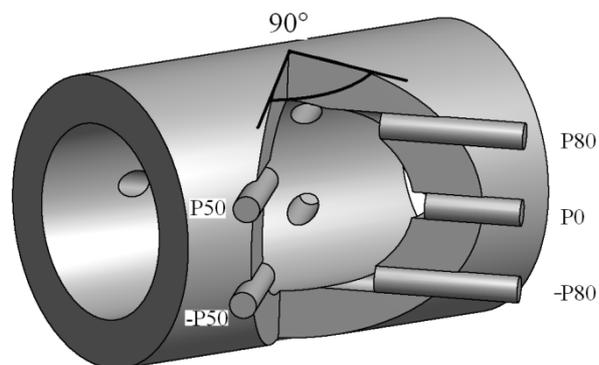


Figure 1 Scheme of an ultrasonic flow meter with five parallel paths at two 45° symmetric planes

## Fully developed turbulent flow profile and ultrasonic flow meters

Following section focuses on UFM used in ideal applications, effects caused by disturbed flow, fluid properties, contamination, or improper maintenance are subject of other publications.

Fully developed turbulent flow profiles (FDFP) exist when the flow velocities do not vary depending on the axial coordinate. We use the model proposed by Gersten [3]. This approach is based on theoretical analysis where its parameters are determined empirically based on experimental data from the superpipe experiment [4]. The result is a dimensionless formulation of the FDFP as a function of the Reynolds number.

In the case of the flow rate facility from the Heat division of the PTB it has been possible to proof that fully developed turbulent flow condition has been reached for the scope relevant to the present study (DN200 at 20°C after an inlet pipe length of 18m). The configuration used for the measurements can be seen in Figure 13.

The Measurements of the flow velocity distribution in the pipe have been performed using a Laser Doppler Velocimeter (LDV). As it can be seen in Figure 2 there is an excellent agreement between the theory and the experimental results.

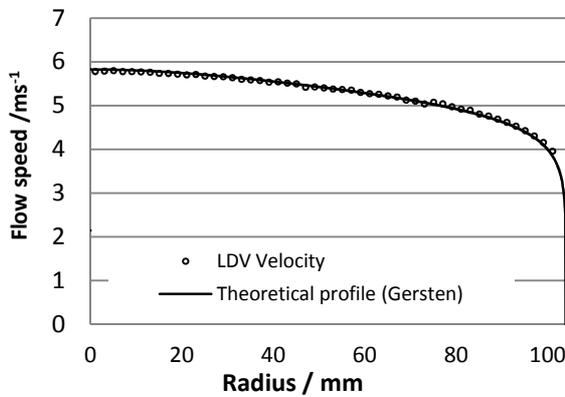


Figure 2 Comparison of the measured with the Theoretical fully developed turbulent flow profile for 600m³/h at 20 °C after 18 m DN200 inlet pipe

Consider a FDFP is measured using an ideal ultrasonic flow meter with an infinite number of parallel paths where the measurement indication of each path is weighed with its length. By plotting these values against the path position Figure 3 is obtained.

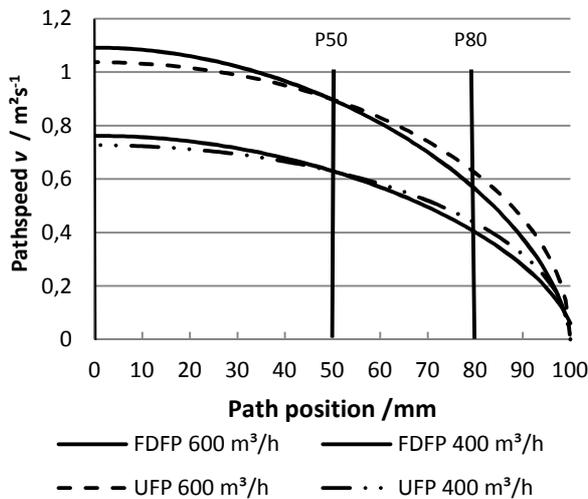


Figure 3 Path mean flows speed weighed to the path length for a DN200 5 path UFM for fully developed flow profile and for a uniform profile at two flow rates 400m³/h and 600m³/h

The solid lines represent 400 m³/h and 600 m³/h. The dotted and dashed lines represent fully uniform flow profiles (UFP). Downstream a reducer, the flow profile gets flat and becomes nearly UFP. From this status it starts develops towards the characteristic FDFP shape; If radial symmetry can be assumed, all flow profiles occurring between an UFP and a FDFP will stay very close to these curves; Therefore, it is expected that conclusions applicable for FDFP can also be applied to radial symmetrical nearly fully developed flow profiles.

By normalizing Figure 3 through the actual flow rate Figure 4 is obtained. Note that the shapes of the path mean velocities P0, P50 and P80 of a FDFP almost remain constant (horizontal lines).

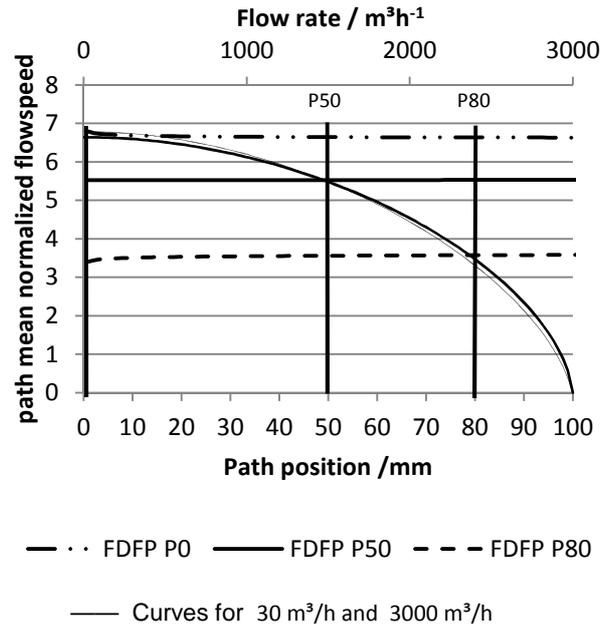


Figure 4 Path mean flow speed scaled with the length of the path and normalized to the actual flow rate for any path position for DN200, plotted in the secondary upper horizontal axis also against the flow rate for P0, P50 and P80.

Since the error curve of an ultrasonic flowmeter is given by a linear combination of P0, P50 and P80, Figure 4 makes clear that the shape of the error curve is robust against weighing factor variations. This condition makes it possible to optimize weighing factors without sacrificing linear response.

### Weighing factors

In the case of an ideal flow meter, the flow rate of an UFM is given by the following expression:

$$Q = \sum_{i=1}^5 w_i v_i \quad (1)$$

$v_i$  is some value proportional to the path mean flow speed and  $w_i$  the weighing factors. Eq. 1 do not include any correction or compensation terms or factors.

The calculation of the weighing factors  $w_i$  is typically based on ideal flow conditions, i.e. secondary components in the measurement volume, secondary components inside the transducer pockets and turbulence effects are neglected. By applying these assumptions, the problem gets reduced to a quadrature integration. See for example [5]. The following section will propose a different approach to the quadrature integration by considering the neglected influences.

## Traceability & weighing factors

In a wide sense, traceability can be obtained through a more or less black-box method called calibration, or it can be guaranteed through modelling as in the case of primary standards. When calibration is preferred, the obtained traceability is valid only for the test conditions. Under test conditions we understand typically a constant FDFP.

As seen in Figure 4, for FDFP the error curve is nearly independent of the flow rate. But when asymmetric flow profiles exist, this independency is not given resulting in the loss of traceability. In the case of industrial or commercial applications, where pipe configuration, fitting of internal diameter, gap free installation and alignment are not always realisable, traceability cannot be guaranteed unless the flow profile is known through measurement, or if it can be guaranteed through pipe configuration.

Assuming the flow profile is known, i.e. all velocity components are known across the pipe section and inside of the measurement pockets, in order to measure the flow rate using a linear combination of the ultrasonic paths, the weighing factors have to be capable to simultaneously maximize the knowledge about the flow rate (the left summation of eq. 2), and minimize the negative effects or errors (the right summation of eq. 2).

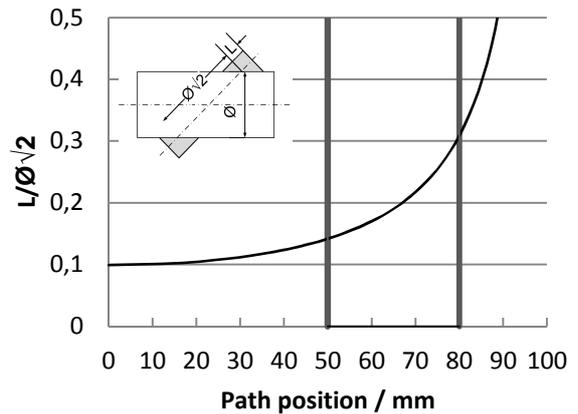
$$Q_{real} = \sum_1^5 w_i v_i + \sum_1^5 w_i e_i \quad (2)$$

## Pocket size

Due to its working principle, TOF based flow meters are equally sensitive to secondary components as they are to axial components. In the case of secondary components occurring in the flow area as swirl for example, there are techniques to reduce and even to cancel out its effects [2]. But in the case of secondary components occurring outside of the measurement volume, inside of the pockets, there is no way to reduce this effect.

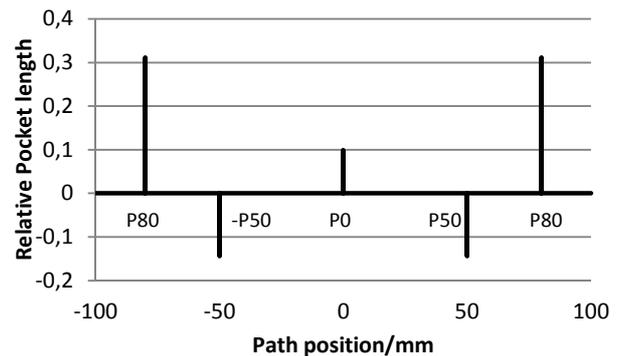
Accurate models and simulations of this effect that could be used to estimate the error have not been published yet. In this analysis we use the size of the pockets as an initial estimator of the error.

The following figure shows the length of the route of the ultrasonic path outside the measurement volume for a typical DN200 ultrasonic flow meter. Note that for P80, the length of the route inside of the pocket is about 30% of the length of the measurement volume.



**Figure 5 Pocket length to Nominal diameter ratio**

The velocity profile occurring inside of the pockets, in spite of not being contributing to the flow, will have a considerable influence on the path transit times. P0, and +/- P80 have a positive angle, +/- P50 has a negative angle. If we consider that the same path inclination angle (+ 45° or - 45°) will produce an error with the same sign, and assuming also that the magnitude of the error grows with the size of the pocket, following figure gives an impression of how the additional pocket flow error is influenced by the weighing factors.



**Figure 6 Estimation of the additional flow error given due to the pocket influences.**

The aim of the weighing factor estimation should be the minimisation of the total additional error. Larger weights at the outer paths are not favourable.

The error induced by this effect decreases for larger diameters as it can be seen in Figure 7.

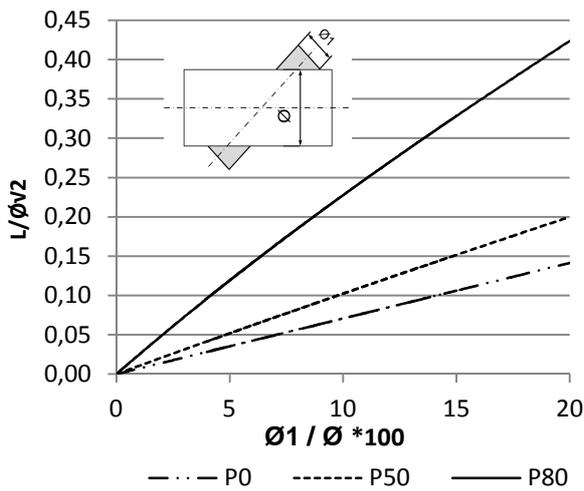


Figure 7 Path pocket length for different pipe-pocket diameter relations.

### Influence of turbulence

The Influence of turbulence on flow meters have been studied in other publications, see for example [8,9], in the case where the fluid speed is much lower than the speed of sound according to Yeh [8], its biasing effects can be neglected. But when considering the accuracy of instantaneous flow indication is important, additional consideration might be necessary.

The turbulence intensity of the flow can be inferred from the standard deviation of the path flow speed. Figure 8 shows the standard deviation of axial velocity measured using LDV.

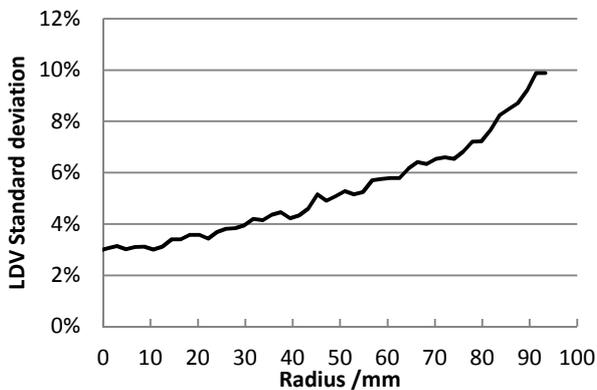


Figure 8 Experimental standard deviation of the LDV measurement for 600 m<sup>3</sup>/h and 18m DN200 inlet pipe length

Table 1 Standard deviation of each ultrasonic path

m <sup>3</sup> /h	-P80	-P50	P0	P50	-P80
300	3,9%	2,2%	1,8%	2,2%	3,6%
370	3,8%	2,1%	1,8%	2,1%	3,4%
450	3,7%	2,0%	1,7%	2,0%	3,3%
575	3,7%	1,9%	1,6%	1,9%	3,2%
750	3,5%	1,8%	1,5%	1,8%	3,1%

It can be observed in Figure 8 and in Table 1, that the outer paths are more influenced by turbulence than the

central paths. The values of LDV are much larger since UFM has an averaging effect trough the path.

### Estimation of weighing factors

#### Turbulence influence reduction

Assuming autocorrelation is neglectable, the instantaneous accuracy of the flow rate is given by:

$$\sigma_Q^2 = \sum_1^5 \sigma_{v_j}^2 w_j^2 \quad (3)$$

Based on the single path standard deviations, it is possible to find a set of weighing factors that maximize the accuracy of the instantaneous flow rate.

By forcing the sum of the weights to have a fixed value to avoid a trivial solution, and by applying the Lagrange multipliers to fulfil this constrain, it is simple to proof that the ideal weighing factors  $w_i$  that minimize the standard deviation of the resulting instantaneous flow rate are defined by:

$$w_i = \frac{\frac{k}{\sigma_i^2}}{\sum_1^5 \frac{1}{\sigma_j^2}} \quad (4)$$

Where  $k$  is a constant and  $\sigma$  are the standard deviations of the path mean flow speeds in m<sup>2</sup>/s. The solution is dimensionless and has to be adjusted by the use of  $k$ .

The same solution can be found numerically by solving the over-determined system of equations resulting from the single vectors of the mean flow speed occurring in a defined time period, and a flow rate vector. In order to minimize the standard deviation, instead of building this vector with the single flow rates corresponding to each mean flow speed vector, the average of the in the time period occurring instantaneous flow rates is used for all. This procedure has the advantage that possible correlations are considered.

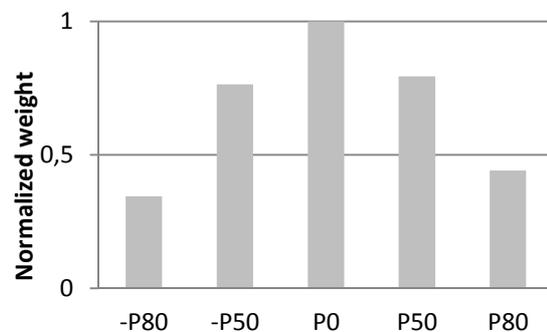
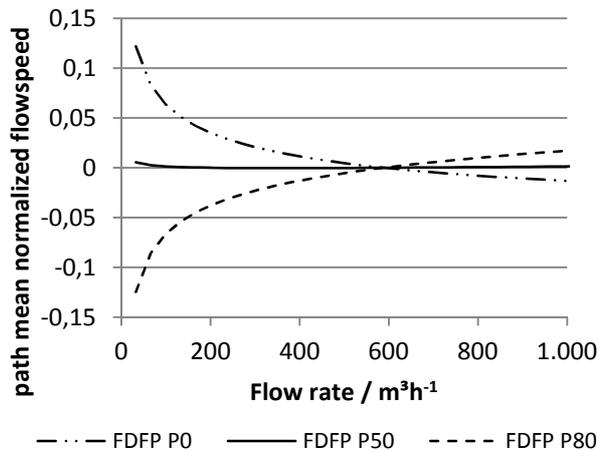


Figure 9 Weighing factors optimized to improve the accuracy of the instantaneous flow rate indication of UFM

**Additional consideration for lower flow rates**

Following figure is based on Figure 4, rescaled and with all curves shifted to be zero at 600 m<sup>3</sup>/h.



**Figure 10** Flow rate dependence of each path shifted to be zero at RE=1E6 about 600 m<sup>3</sup>/h at 20°C

From the curves P0 and P80, it is possible to state a relation for a zero error behaviour of the flow rate by making

$$P0 + 2\alpha P80 = 0 \quad (5)$$

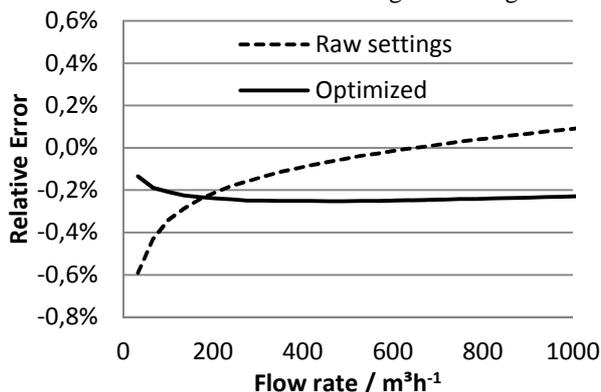
$$\alpha = 0,318 \quad (6)$$

$$w_{P0} = 0,318 \quad w_{P80} = 0,318 \quad w_{-P80} \quad (7)$$

If Eq. 7 is satisfied a good performance is to be expected in flow rates below 400 m<sup>3</sup>/h. This condition is almost given by the proposed weights (Figure 9).

**Initial Results for the new weighing factors**

By applying these factors to the theoretical FDFP we obtained the theoretical error curves given in Figure 11



**Figure 11** Theoretical error produced by an ideal five path DN200 UFM using raw and optimized weighing factors

None of the weighing factor sets deliver a zero-error, but since for this application, the UFM will be used as a comparator, a zero-error is not necessary; instead an almost constant error is preferable.

The obtained factors have been also tested at extreme conditions in the flow test rig of the heat laboratory of the

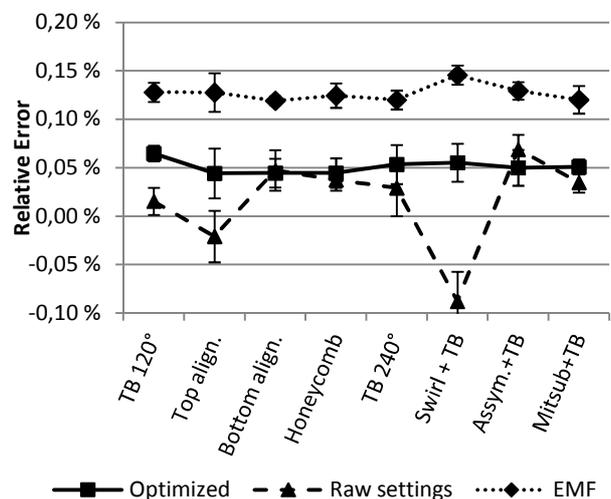
PTB in Berlin. Several configurations that might occur when an ideal set up has been intended, have been tested according to Table 3.

**Table 2** General Specification of the Flow Laboratory in Berlin

Flow rate	DN80 – DN 400 3 m <sup>3</sup> /h up to 1000 m <sup>3</sup> /h
Temperature range	3°C up to 90 °C
Temperature drift	< 50 mK/h
Reynolds number	up to 5 × 10 <sup>6</sup>
Measuring sections	25m
Flange mismatch	< 50 μm
Pipe roughness	< 0.5 μm
Relative uncertainty	< 4 × 10 <sup>-4</sup> (k=2)

**Table 3** Flow configurations for the tests in Berlin

TB 120°	Tube bundle flow conditioner rotated 120°
Top align.	Intentional positive misalignment of the upstream pipe connection
Bottom align.	Intentional negative misalignment of the upstream pipe connection
Honeycomb	A honeycomb flow conditioner has been used.
TB 240°	Tube bundle flow conditioner rotated 240°
Swirl + TB	Swirl generator has been installed before the Tube bundle
Assym.+TB	Strong asymmetry has been installed before the tube bundle
Mitsub+TB	Mitsubishi type flow conditioner has been installed before the tube bundle



**Figure 12** Sensitivity test at 80 °C and 400 m<sup>3</sup>/h

**Bilateral comparison using the new configuration**

The laboratory of heat, and the laboratory for fluid flow of the PTB have an overlapping working range at 20°C and up to 1000 m<sup>3</sup>/h. Within this range, it is a high priority to guarantee comparability. For this purpose, the new weighing factors have been applied to the flow meter and a bilateral comparison has been organized using the treated UFM in DN200 at 20°C and

between 400 m<sup>3</sup>/h and 1000 m<sup>3</sup>/h. For more details on the flow laboratories of the PTB refer to [6,7]

The Measurements were performed between 400 m<sup>3</sup>/h and 1000 m<sup>3</sup>/h and at 20°C. The pipe layout can be extracted from Figure 13. Measurements have been performed with and without flow conditioner. The reason for this is that FDFP can turn easily asymmetric if for example a flange mismatch remains undetected. In this case, only the measurements with flow conditioning would be valid.

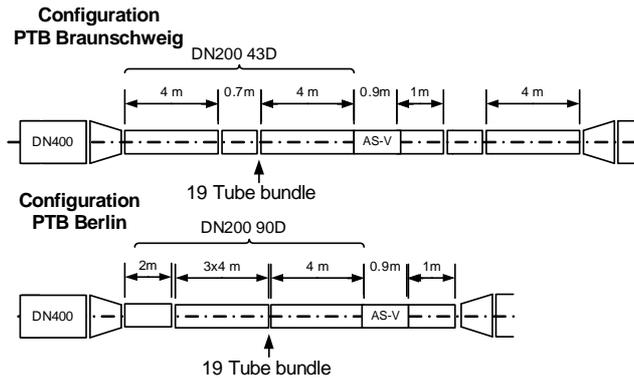


Figure 13 Pipe layout at Berlin and Braunschweig

In order to see the performance of the weighing factors, both weighing factor sets have been considered.

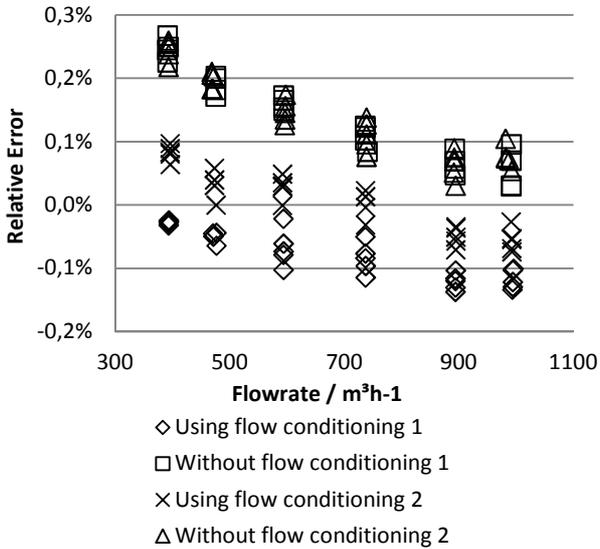


Figure 14 Measurement results in the laboratory at the PTB-Braunschweig All single measurement results are showed.

The results of the raw weighing factors seen in Figure 14 spread in a wide band of about 0.25%. The expected band (peak to peak) is less than 0.1%.

When the new weighing factors are applied, the spread reduces down to 0.1% as a peak to peak value as seen in Figure 15. These are excellent results, considering that two different configurations with and without tube bundle are included.

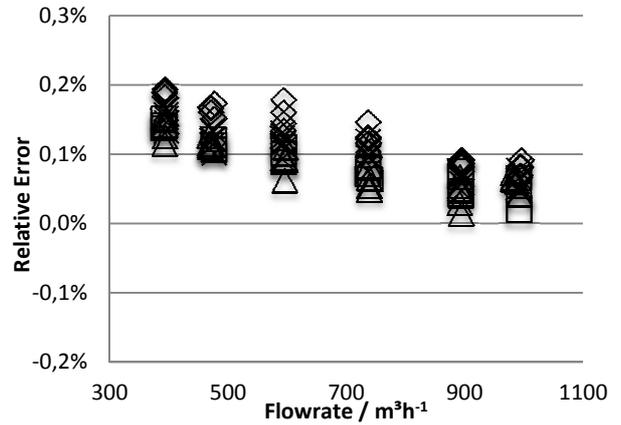


Figure 15 Results after applying the optimized weighing factors

During data processing, for the measurements without tube bundle, the data spread between Berlin and Braunschweig was unexpectedly large. After a short investigation, it was discovered that during the installation of the package in Braunschweig, the temperature sensor from Figure 16 was not removed from the test line, causing a considerable asymmetry. This forced us to discard the measurements without flow conditioners since the symmetry condition was not fulfilled any more.



Figure 16 DN200 Disturbance and Tube Bundle

The final results of the comparison are shown in Figure 17. The new weighing set reflects the expected comparability of the flow laboratories under 0.02%.

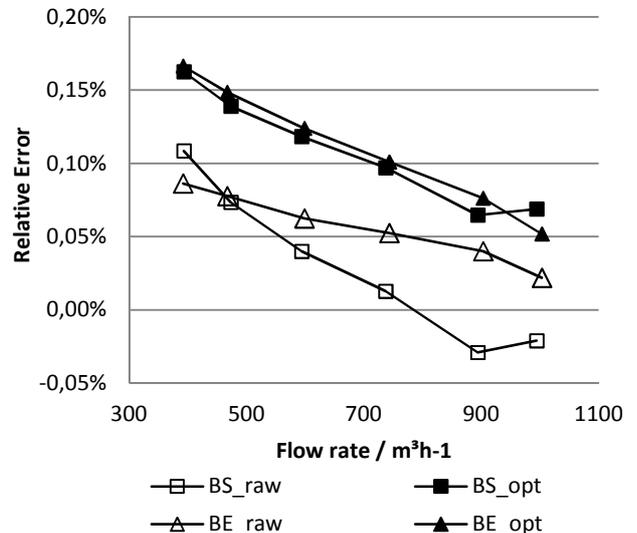


Figure 17 Final results of the comparison within the PTB. The maximum deviation Between PTB-Berlin und PTB-Braunschweig is under 0.02%

## **Discussion**

By observing Figure 17 it is inevitable to think about the validity of the selected weighing factors. Is it possible to play with the weighing factors, until the desired result comes out? The answer is up to a certain point: Yes, but according to our experience, this is not very likely to happen. The most important question to ask would be: how to proof that certain weighing factors are correct or incorrect? The weighing factors presented in this paper, are derived analytically, arguments are presented why this set of weights could improve the measurement results; nevertheless, they cannot explain exactly the reason for the shapes of the obtained curves.

In order to answer this question, it will be necessary to perform more experiments. That the accuracy of UFM is guaranteed to be under 0.2% is state of the art, but in order to reach values far below 0.1% more knowledge about the structure of the flow is necessary.

It has been seen in Figure 12 that different positions of the tube bundle results in different results, what initially suggests that flow conditioners are necessary only when strong disturbances are present. But considering the fact that using a flow conditioner delivers good results, in this case even more reliable than those without flow conditioners, it is recommended for interlaboratory comparisons to use both configurations, if high reliability is required.

## **Summary and further work**

For the application in interlaboratory comparisons, it has been shown that it is possible to vary the values of the weighing factors without having to renounce to linearity when a nearly fully developed flow has been reached.

By means of a qualitative consideration of the possible error sources the behaviour of the error curve when the weighing factors are varied has been analyzed. It has been shown that if the right weighing factors are selected, the errors caused by secondary components inside of the pockets can be cancelled out.

A new set of weighing factors that per definition improves the instantaneous accuracy of the flow rate indication has been calculated. This set may also fulfil the requirements to cancel out effects of the pockets. This has been shown in a bilateral comparison organized by two internal laboratories of the PTB with outstanding results.

Nevertheless, in order to proof the validity of a universal application, more experiments and measurements are necessary, since neither the actual secondary components inside of the pockets, nor the secondary components within the measurement volume have been measured yet.

## **References**

- [1] N. Furuichi, H. Sato, Y. Terao, M. Takamoto "A new calibration facility for water flowrate at high Reynolds number" Flow Measurement and Instrumentation, 20 (1) (2009), pp. 38–47
- [2] J. Drenthen, M. Kurtz J.van Klooster, M. Vermeulen "Reducing installation effects on ultrasonic flow meters" 7th International Symposium on fluid Flow Measurement, 2009
- [3] W. Merzkirch (Ed.), "Fluid Mechanics of Flow Metering" Heidelberg: Springer Verlag 2005 Ch1 pp 1-22
- [4] McKeon BJ, Li J, Jiang W, Morrison JF, Simts AJ, "Further observations on the mean velocity in fully developed pipe flow. J. Fluid Mech 501, pp135-147
- [5] C. N. Pannel, W. A. B. Evans, D. Jackson, "A new integration technique for flowmeters with chordal paths" Flow Measurement and Instrumentation. Vol 1 July 1990
- [6] R. Engel PTB's "Hydrodynamic Test Field - Investigations to Verify the Measurement Uncertainty Budget" FLOMEKO 2004, Guilin, China,
- [7] Mathies, N. "Messunsicherheit einer gravimetrischen Kalt- und Warmwasser- Normalmessanlage für große Volumenströme" Dissertation, Technische Universität Berlin 2005 Mensch & Buch Verlag Berlin
- [8] T. T. Yeh and G. E. Mattingly, "Computer simulations of ultrasonic flow meter performance in ideal and non-ideal pipeflows", Fluids Engineering Division Summer Meeting FEDSM 1997
- [9] Strunz T, Wiest A, Fleury A, Fröhlich T. "Influence of turbulence on ultrasonic flow measurements" 5th IGHEM conference 2004. Lucerne 2004.