Main Index

North Sea FLOW Measurement Workshop

Paper 24: 4.4

DISTURBED FLOW PROFILES AND THEIR EFFECT ON GAS METER BEGAVIOUR

- SYSTEMATIC INVESTIGATIONS AND PRACTICAL CONCLUSIONS-

Authors:
Gudrun Wendt, Bodo Mickan, Rainer Kramer and Dietrich Dopheide
Physikalisch-Technische Bundesanstalt (PTB) Braunschweig, Germany

Organiser:
Norwegian Society of Chartered Engineers
Norwegian Society for Oil and Gas Measurement
Co-organiser:
National Engineering Laboratory, UK

DISTURBED FLOW PROFILES AND THEIR EFFECT ON GAS METER BEHAVIOUR

- SYSTEMATIC INVESTIGATIONS AND PRACTICAL CONCLUSIONS -

Gudrun Wendt

Bodo Mickan, Rainer Kramer, Dietrich Dopheide

Physikalisch-Technische Bundesanstalt (PTB) Braunschweig, Germany

Summary

Within the scope of an extensive PTB research project a special facility was built which allows the investigation of flow profiles downstream of several pipe geometries and flow straighteners. Modern and effective miniaturized semiconductor based laser Doppler techniques are used to measure the developing velocity profiles inside the pipe sections of interest. The corresponding reaction of turbine gas meters is determined with a high accuracy and repeatability using the PTB's flowrate standard facility with critical nozzles. Until now more than 150 different flow distributions have been investigated. The results are summarized in a flow profile catalogue which shows the high degree of systematics and generality of the work.

On the basis of these results it has become possible to achieve good transparency of the flow processes taking place in real gas pipe configurations and to explain the mechanism of the interaction between characterictic flow distributions and turbine meter performance.

The conclusions concerning the active conditioning of disturbed flows in particular allow optimized pipe lengths and flow conditioners to be recommended with a view to minimizing or eliminating the influence of flow disturbances on the flowmeter behaviour.

1 INTRODUCTION

It is a well-known fact in flow measurement that the behaviour of the measuring devices used can be affected very seriously by the flow conditions prevailing at their inlet pipe section. Different pipe configurations such as for instance bends, headers, pressure regulators, or changing diameters generate different distributions of the fluid's flow velocity and turbulence intensity. The concrete effect of these „disturbed" conditions on the measuring behaviour of a flowmeter installed downstream depends basically on the working principle of the meter itself. The resulting deviation in the meter reading can amount up to several percent.

The whole phenomenon of the so-called installation effects in flow measurement appears as a very complex and complicated problem: on the one hand the measuring practice shows a wide variety of pipe geometries and duct configurations, and on the other hand the different types of flowmeters react in very different kinds to the flow conditions at their inlet. That's why there are an actual need and a great interest in investigating and understanding the physics of the chain „pipe configuration - disturbed flow profile - change in flowmeter behaviour" with the final aim to find out effective methods and techniques to minimize the installation effects.

In the last few years many efforts were already made in this particular field of flow measurement. An analysis of the relevant publications shows that emphasis was placed predominantly on three aspects:

- Investigations into the concrete effects of special pipe configurations on the behaviour of special flowmeter types installed downstream (orifice metering installations [1-3], turbine meters [4,5], ultrasonic and electromagnetic flowmeters [6], or vortex flowmeters [7]).
  In some cases the measuring errors due to the flow disturbances tested are described as of a remarkable order of up to 5 % for orifice and turbine meters [8] or of up to 11 % for ultrasonic flowmeters [9].

- Study of the performance of different flow straighteners and conditioners such as perforated plates, tube-bundle, Zanker, or Etoile flow conditioners and of their efficiency for the reduction of flow disturbances and the establishment of nearly ideal flow conditions with well developed velocity and turbulence profiles.
  The respective publications describe the effect on both the flow profiles [10-12] and several complete flowmeter performances [13,14].

- Description of the methods for investigating the flow characteristics and their development downstream of the pipe configurations and flow conditioners to be investigated.
  In addition to the more conventional methods such as Pitot tubes [15] or hot film probes [14,16], laser methods are employed in a wide range of application, using, for example, Laser Doppler Anemometry (LDA) [4,10,17-18] or Particle Image Velocimetry (PIV) [19]. Recently the development of flow phenomena in pipes are studied by means of Computational Fluid Dynamics (CFD) [20,21] where a numerical simulation of the pipe flow gives, for example, obvious pictures of the complete velocity distributions in the pipe section of interest.

Most of the publications concerning the problems of flowmeter installation effects are, however, confined to the investigation of very individual cases: special pipe configurations, special flow distributions, and special flowmeter performances. A general systematic analysis of the whole interaction chain from certain pipe configurations through developing flow distributions to the resulting meter behaviour has been lacking. Therefore, a PTB research project sponsored by the DVGW (Deutscher Verein des Gas-und Wasserfachs) was initiated as a first step towards filling this gap. The main aims were:

- Experimental investigation of all practically relevant pipe geometries and flow phenomena developing downstream including the investigation of their decay, systematization and generalization of all data obtained

- Definition and quantification of flow characteristics describing the types of resulting perturbations such as swirl intensity, skewness, and asymmetry of the velocity profiles

- Determination of the deviations in the reading of various flowmeters (starting with turbine gas meters)

A solution of the installation effect problem is conceivable in two directions:

- Development of an empirical model to explain the metering effects and to predict, if possible, the expected shift in the meter reading

- Investigation of the efficiency of various types of flow conditioners and, if need be, development of optimized forms of conditioners in dependence on the perturbation and flowmeter typ

2 LDA DIAGNOSTIC FACILITY FOR INSTALLATION EFFECTS

At the first stage of the project the activities concentrated on the investigation of turbine gas meters working with air at atmospheric conditions. To carry out all experimental work mentioned above a special automated test facility was built.

This diagnostic facility takes advantage of two developments successfully pursued at the PTB in the last few years - first, the extensive research on laser techniques and the construction of efficient LDAs, and secondly, the use of critical nozzles for the establishment and measurement of the gas flow with a very high accuracy and reproducibility. It has thus become possible to combine the detailed knowledge of the flow characteristics inside the pipe infront of the flowmeter (including its inlet section) with the exact information about the behaviour of the flowmeter itself.

The LDA diagnostic facility (Figure 1) consists of the following main elements:

- the installation configurations to be investigated (for example, single or double bends, convergent or divergent sections, half plates, flow conditioners, various straight pipes up to 40 diameters in length, etc.)
- the optical test unit consisting of a two-component semiconductor LDA system to measure the flow profiles in the entire cross section of the pipe and a special pipe segment which allows the optical access to the flow inside the pipe
- the gas meter to be investigated
- the flowrate standard consisting of eight critical nozzles to determine the gas meter's dependence on the inlet flow profiles

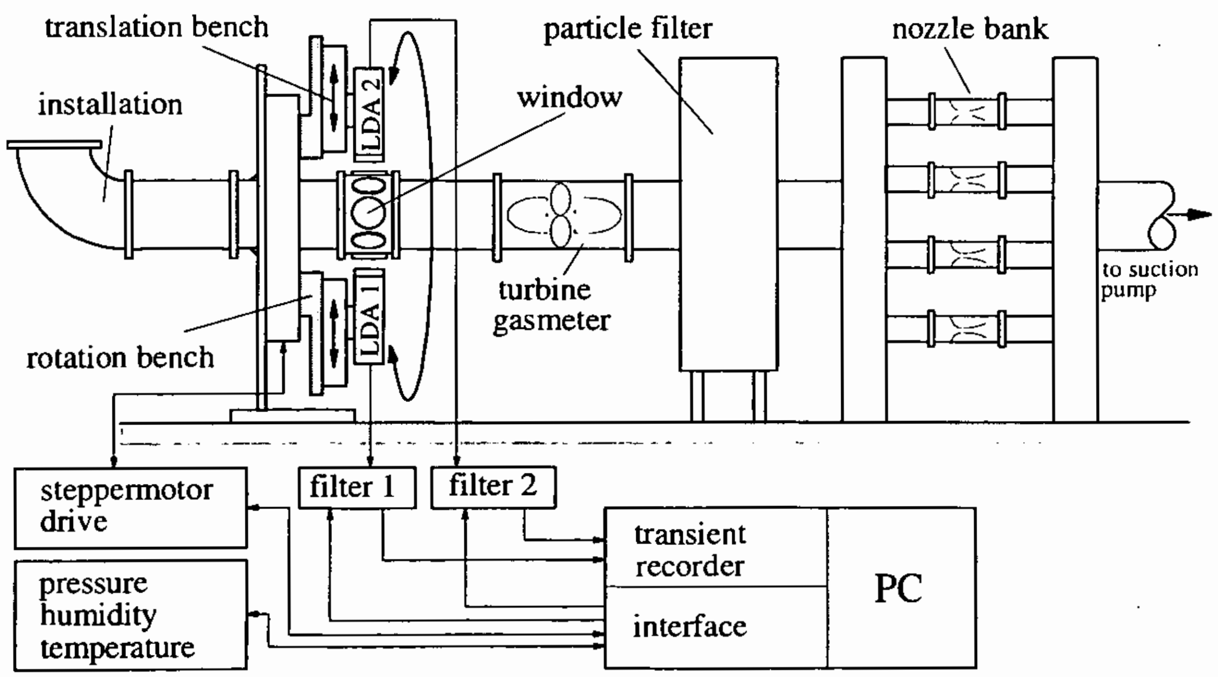


Fig. 1: Schematic view of the computer-controlled facility to investigate installation effects

This facility shows some specialities ensuring an uncomplicated and practice-related work. Free inlet and suction method for gas flow generation allow pipe configurations of any kind and size to be easily installed in a short time. This is, for example, an advantage over closed conduits as used in liquid or high pressure gas measurements. A second important characteristic of this facility is the large-scale simulation of the flow conditions actually encountered in industrial gas distribution and measuring systems. Most of the investigations in the past were carried out under ideal conditions using ideally fashioned pipework. In contrast to this, all pipe elements and devices used at PTB were taken from regular fabrication with common roughness characteristics and production tolerances. In this way it will be possible to transfer the test results directly to practical application.

The most important part of the facility is the LDA measuring unit. The connection to the piping is realized by a special pipe segment (Figure 2). Eight windows allow four different profiles rotated by 45 ° to be scanned. Inside the pipe, each window is made of a glass film to prevent changes in the diameter and to provide for a smooth inner contour of the pipe. The windows outside the pipe consist of plane glass plates to block pressure differences.

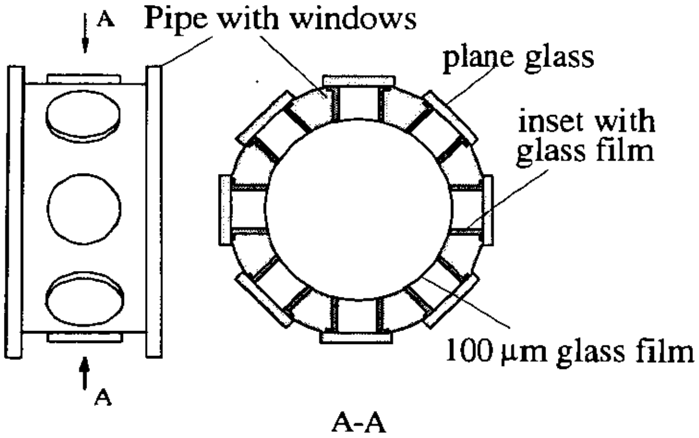


Fig. 2: Schematic view of the special pipe segment with outer glass windows and a smooth inner wall contour using thin glass films

Two separated LDAs for the two-dimensional measurement of the flow profiles are installed on a rotating mechanism and positioned face to face on both sides of the pipe segment described. Each miniature diode LDA is mounted on a precise linear traversing bench and can be operated by a remote control. A linear scan through the pipe diameter is easily done when moving tables are driven synchronously.

Remote control and automation of the facility covers the LDA acquisition system based on transient recorder plug cards for PC/AT, control of the positioning devices, setting of the flowrate, reading of the gas meter and acquisition of the state of flow, i.e. pressures, temperatures, humidity etc. The software extracts information relevant for the configuration of the set-up from parameter tables compiled by experience and it is able to perform complete velocity profile measurements completely automatically.

The main characteristics of the LDA test unit used for the experiments are:

Pipe diameter	DN 200
LDA-system	2 one-component semiconductor LDAs in forward scatter mode
Wavelength	780 nm and 830 nm
Colour splitting	optical filters
Velocity uncertainty	< 1 %
Acquisition	two channel transient recorder card, sample rate 100 Mhz
Number of sample points	1028 for each LDA and each measuring point

A particle filter installed downstream of the flowmeter to be tested protects the nozzle standard from deposition of seeding material necessary to produce scattering particles for the LDA.

The generation of a stable and well-known flowrate is realized by a nozzle bank consisting of eight critically nozzles with individual flowrates between 65 m^3/h and 2500 m^3/h, and a maximum flowrate of 5500 m^3/h when all nozzles are used in parallel. The uncertainty for the flowrate generation is less than 0,1 %, its reproducibility less than 0,01 %.

3 FLOW PROFILE MEASUREMENTS

Figure 3 shows the position of the velocity components used for the following presentation of the flow characteristics inside the optical test unit and the direction of the co-ordinate system. The two LDAs are measuring at an angle of + 45 degrees and - 45 degrees each with respect to the x-axis. Knowledge of these two components of the velocity vector allows the axial velocity component *u* and the tangential velocity component *v* to be evaluated as shown in this graphic.

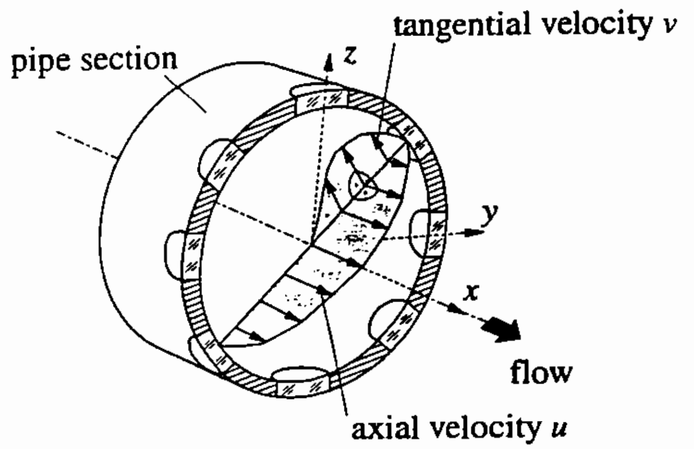


Fig. 3: Positions of the velocity components measured and the co-ordinate system used

In the following some typical pipe configurations (straight pipes of various lengths, single and double bends with constant and changing diameter) and the resulting velocity distributions are presented. They are selected from more than 100 different performances investigated and should give an idea about the kind and amount of data collected. In general, all configurations included in the experimental activities were investigated at various (normally four) flowrates and equipped at least with three different straight pipe lengths (normally 2 D [1], 5 D, 10 D) between the perturbation exit and the flowmeter inlet. The configurations with double bends were measured in both symmetrical arrangements.

The velocity profile measurements were started with the determination of the undisturbed pipe flow conditions as a reference. For this purpose a straight pipe with different lenghts between 2 D and 40 D and free inlet flow was used. The resulting velocity distributions measured showed that a nearly fully developed turbulent velocity profile was obtained downstream of a straight pipe of 28 D long, see Figure 4. The distribution of the axial velocity components follows the theoretically predicted law, tangential velocity components are not visible. These profile parameters were assumed to be undisturbed and served as a basis for all comparisons described below.

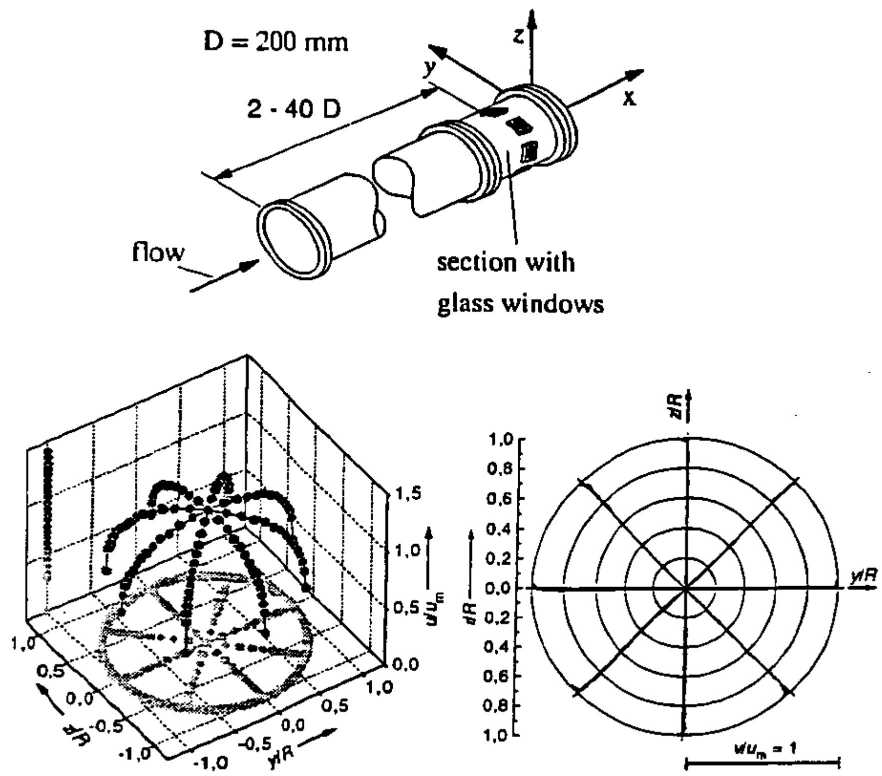


Fig. 4: Schematic view of the straight pipe investigated in different lengths and perspective plot of the axial components u (left picture) and the tangential components v (right picture) of the velocity distributions downstream of a straight pipe of 28 D in length.
Air flowrate $Q = 1750\ m^3/h$; Reynolds number $Re = 1{,}9 \cdot 10^5$
All velocities shown are normalized with the mean axial flow velocity u_m. [2]

The first example (Figure 5) for disturbed flow conditions shows the axial and tangential components of the velocity distribution downstream of a single bend and straight pipe lengths of 2 D and 10 D. At the 2 D distance, the axial velocity profiles show a local minimum at the centre of the pipe and an elevation towards the pipe wall. The tangential velocity distribution at this 2 D distance is in good agreement with the theoretical model describing the generation of two secondary swirls for such a pipe configuration. These

[1] Usually, these straight pipe lengths are expressed in multiples of the inner pipe diameter D.

[2] All profiles treated in the following have been determined at the same flowrate and Reynolds number and are represented in the same graphic view.

disturbances decrease relatively quickly with increasing straight pipe length: At 10 *D* both the axial and the tangential distributions have a shape similar to that under undisturbed conditions. This assumption is supported considering the error shifts of a turbine meter G 1600 used for the described investigations compared with its reading at undisturbed flow conditions: + 0,48 % for the 2 *D* straight pipe between the bend and the meter, + 0,16 % for the 10 *D* straight pipe.

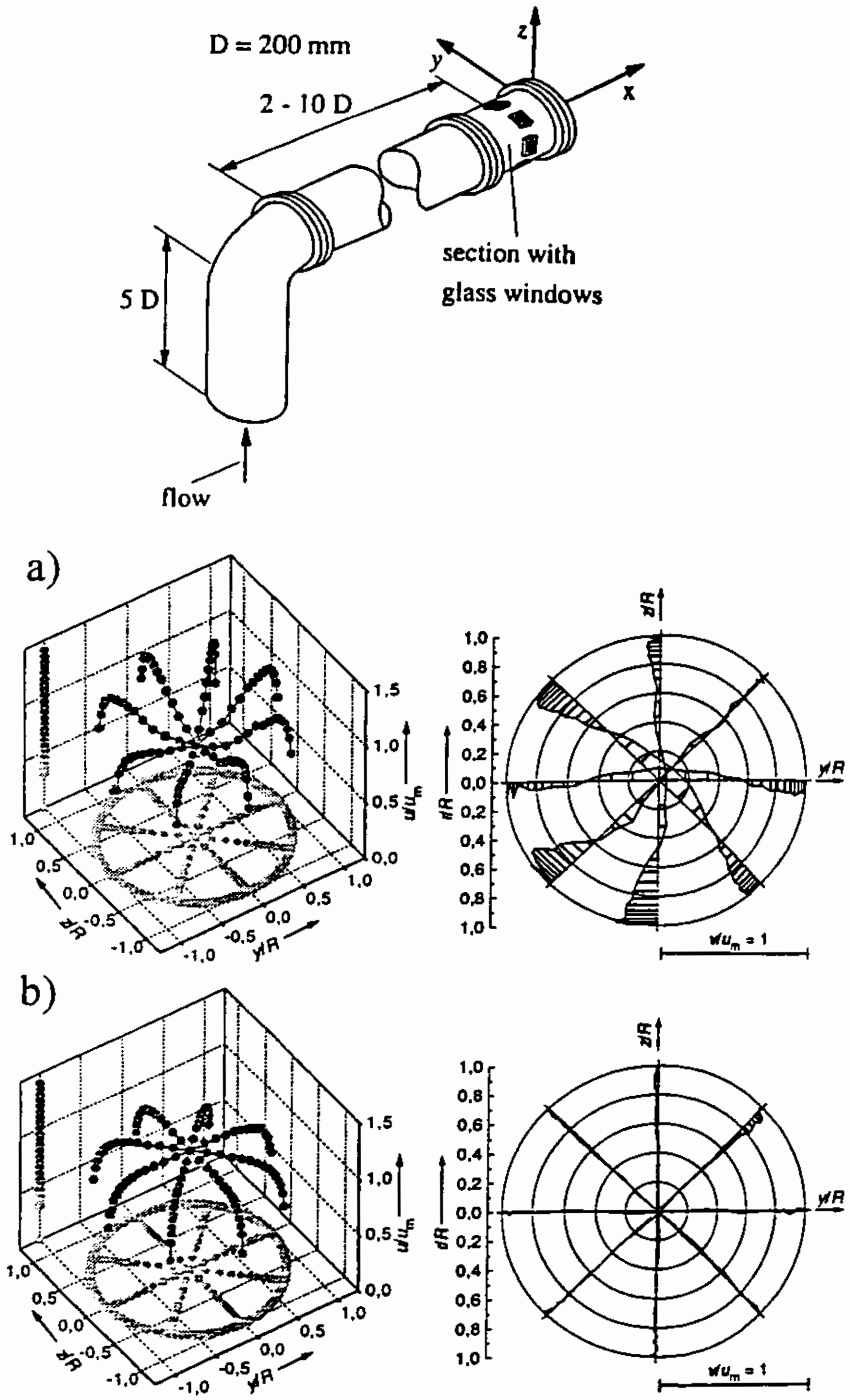


Fig. 5: Schematic view of the pipe configuration investigated and perspective plot of the axial components u (left pictures) and the tangential components v (right pictures) of the velocity distributions downstream of a single bend and a straight pipe of a) 2 D and b) 10 D

The next two figures show the flow characteristics for the same pipe configurations where the single bend has been replaced by a double bend with the diameter remaining unchanged (Figure 6) and a double bend in a reduced diameter, half pipe area plate between the bends and a diverging pipe section connected behind („high level perturbation“ according to OIML R 32 [22] - Figure 7).

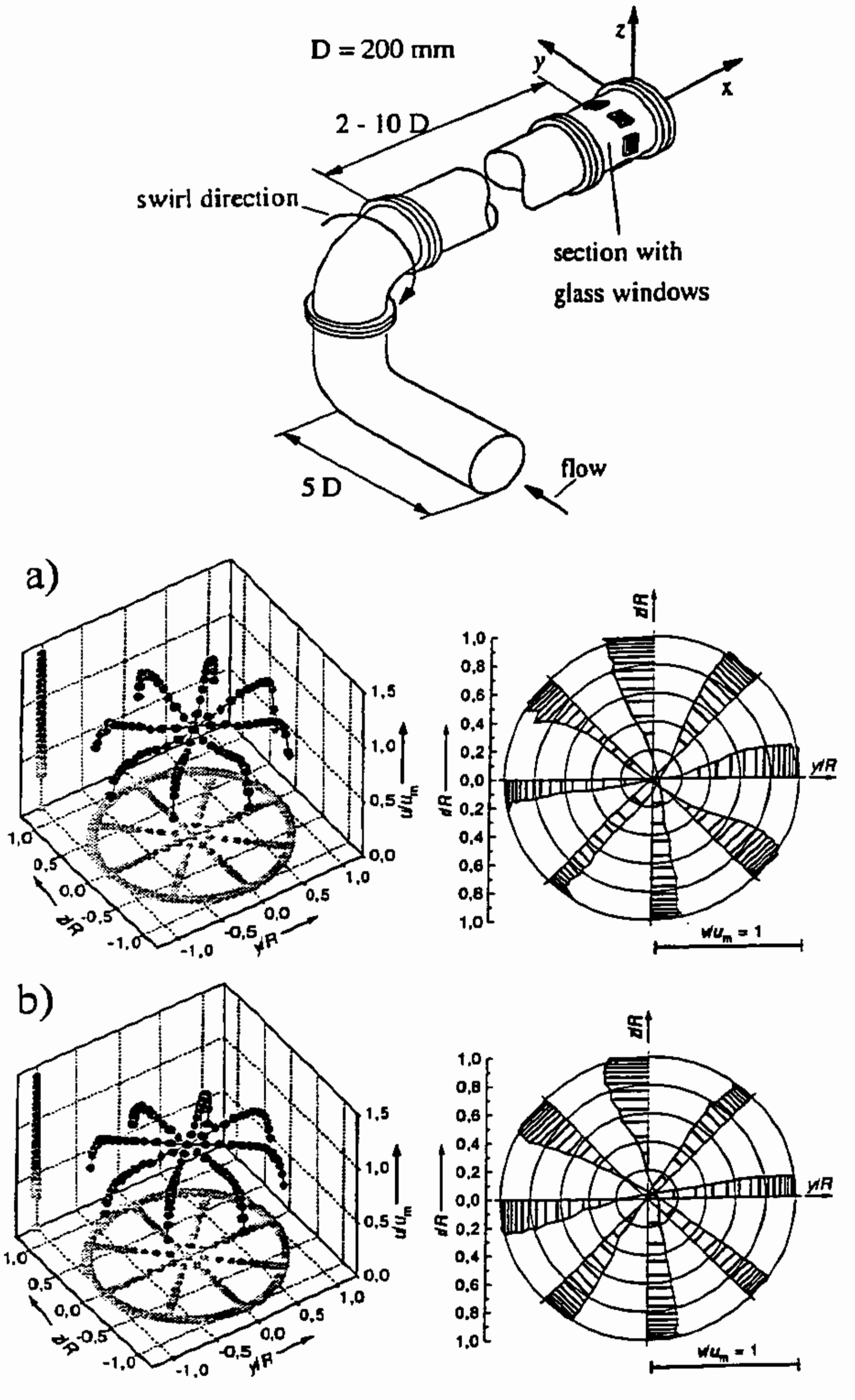


Fig. 6: Schematic view of the pipe configuration investigated and perspective plot of the axial components u (left pictures) and the tangential components v (right pictures) of the velocity distributions downstream of a double bend out of plane with unchanged diameter and a straight pipe of
a) 2 D and b) 10 D

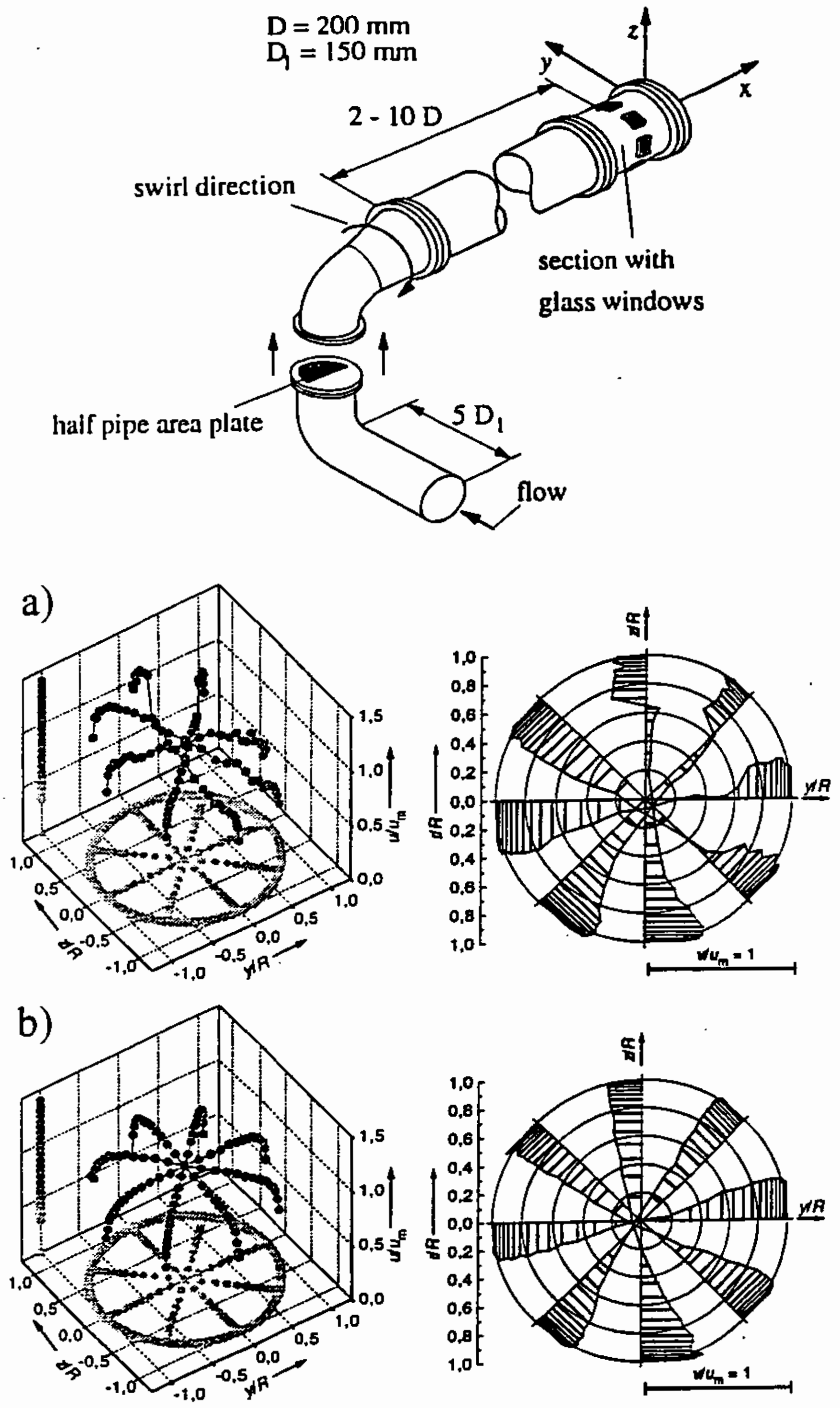


Fig. 7: Schematic view of the pipe configuration investigated and perspective plot of the axial components u (left pictures) and the tangential components v (right pictures) of the velocity distributions downstream of a double bend out of plane equipped with a half pipe area plate („high level perturbation" according to OIML R 32) and a straight pipe of
a) 2 D and b) 10 D

In both cases, the axial velocity profiles are not symmetrical, and the tangential components show swirls and secondary flows of high intensities. These tangential components v reach values of up to more than 40 % of the mean axial velocity u_m. The conspicuously disturbed profiles (discontinuities in the axial and tangential profiles along two traverses) for the 2 *D* high level perturbation in Fig. 7 can be explained by the extremely high turbulence behind the half pipe area plate with reverse flows in the turbulent mixing zone and radial velocity components. Although a normalization of the axial velocity distributions towards the fully developed profile between the 2 *D* and 10 *D* distances is perceptible, the swirls continue to exist with nearly the same order of intensity at the 10 *D* distance.

A comparison of the turbine meter's error shifts for different straight pipe lengths between the perturbation and the meter inlet (Table 1) confirms the statement that a 10 *D* straight pipe is not long enough to effectively diminish the flow perturbations downstream of double bends out of plane.

Table 1: The error shift of a turbine gas meter G 1600 for different pipe configurations and straight pipes of different lengths upstream of the meter, compared with the undisturbed flow (volume flowrate $Q = 1750\ m^3/h$; $Re = 1{,}9 \cdot 10^5$)

	Error shift for straight pipe lengths of		
	2 D	**5 D**	**10 D**
Single bend (Fig. 5)	+ 0,48 %	+ 0,18 %	+ 0,16 %
Double bend out of plane (Fig. 6)	+ 1,13 %	+ 1,15 %	+ 0,88 %
High level perturbation (Fig. 7)	+ 1,37 %	+ 1,32 %	+ 1,08 %

In addition to the flow profiles, the turbulence intensity distributions were determined for all pipe geometries and flowrates investigated. Figure 8 shows some of them for the pipe configurations already described above (straight pipe, single bend, double bend out of plane and high level perturbation).

The turbulence intensity *Tu* was evaluated using the individual values of the axial and tangential velocity components *u* and *v* obtained during the profile investigations and assuming each of these individual values to be the sum of a time-averaged value ($\overline{u}$ or $\overline{v}$) and a instantaneous deviation (u' or v') from this averaged value

$$u = \overline{u} + u' \qquad \text{and} \qquad v = \overline{v} + v' \tag{1}$$

The equation to evaluate the turbulence intensity *Tu* reads as follows

$$Tu = \frac{\sqrt{s_u^2 + s_v^2}}{\sqrt{2} \cdot u_m} \tag{2}$$

where s_u^2 and s_v^2 are the variances of the axial and tangential velocity components *u* and *v*, respectively

$$s_u^2 = \overline{\left(u - \overline{u}\right)^2} \qquad \text{and} \qquad s_v^2 = \overline{\left(v - \overline{v}\right)^2} \tag{3}$$

and u_m is the mean axial velocity through the pipe.

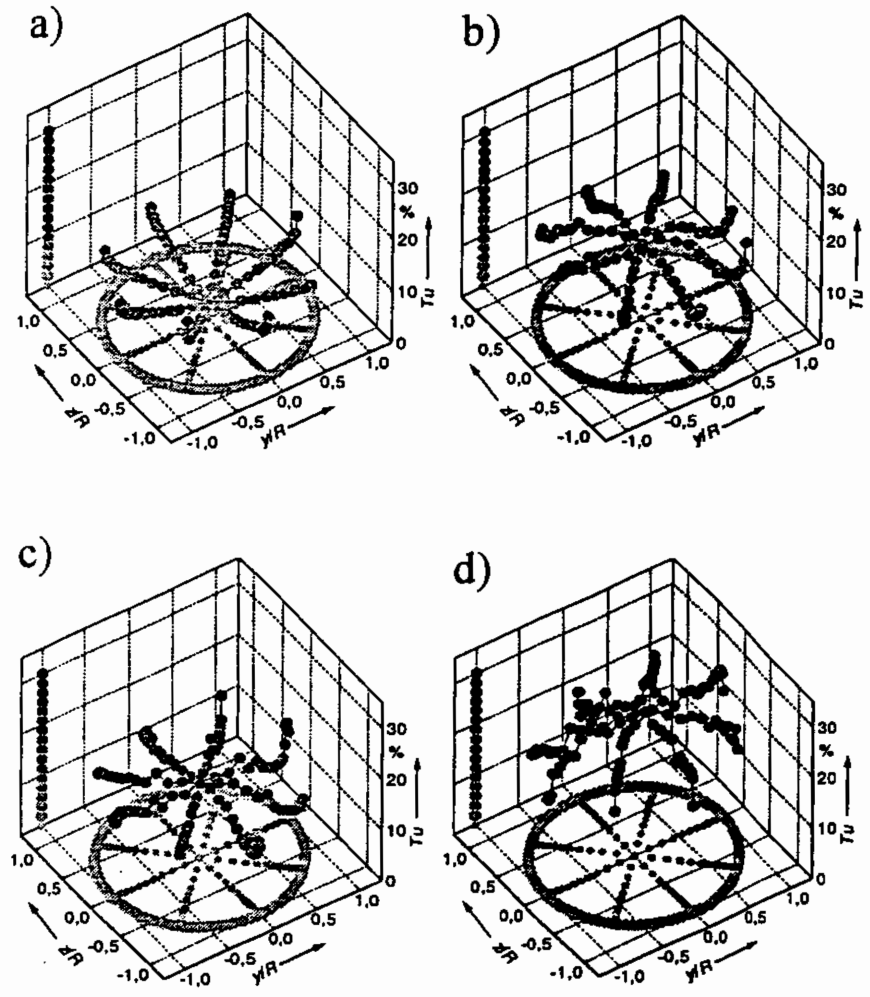


Fig.8: Measured turbulence intensity distributions for different pipe geometries
a) straight pipe of 28 D according to Fig. 4
b) single bend and 2 D straight pipe according to Fig. 5
c) double bend out of plane and 2 D straight pipe according to Fig. 6
d) high level perturbation and 2 D straight pipe according to Fig. 7

In the case of a straight pipe (Figure 8a) one recognizes a symmetrical degree of turbulence with a minimum in the centre of the pipe and higher turbulence intensities towards the wall as it is well known from literature. The turbulence intensity significantly increases in the core region when a single bend is applied (Figure 8b). A double bend out of plane as shown in Figure 8c provides for a much more asymmetrical turbulence distribution. The worst case is to be seen at the high level perturbation in Figure 8d where a very asymmetrical high level turbulence is to be observed.

The results of the investigations decribed in the previous chapter have led to important conclusions regarding the interaction chain between pipe geometries, developing flow distributions and the resulting behaviour of the flowmeter (namely the shift of the error curves). They have given a vivid picture of the processes taking place in the various pipe elements impressive investigated. Nevertheless, this knowledge is not enough to reach the real goal - to improve flow measurements in general and, if possible, to avoid measurement mistakes at all.

There are two approaches to continuing the work making use of the experience and knowledge gained:

- first, to use suitable mechanical damping elements to influence the flow in such a way that, at the flowmeter inlet, the velocity profiles are nearly undisturbed and do not affect the meter reading. This method requires additional pipe installations (such as, for example, flow starighteners or conditioners), but it is independent of the flowmeter type;
- secondly, to try to describe mathematically the correlations found, to develop a corresponding model, and to predict and consider the changes in the flowmeter behaviour in dependence on the flowmeter type and the actual pipe configuration.

4 FLOW CONDITIONER INVESTIGATIONS

To prove that it is possible to provide for an efficient flow conditioning, another large series of experiments was carried out. Several types of flow straighteners and conditioners were investigated and evaluated with regard to their efficiency to reduce flow disturbances generated by the pipe configurations described above. Fig. 9 shows the most important types of flow conditioners examined: Etoile, Zanker, and tube-bundle conditioners as well as perforated plates of different kinds in various combinations (single, double, triple plates).

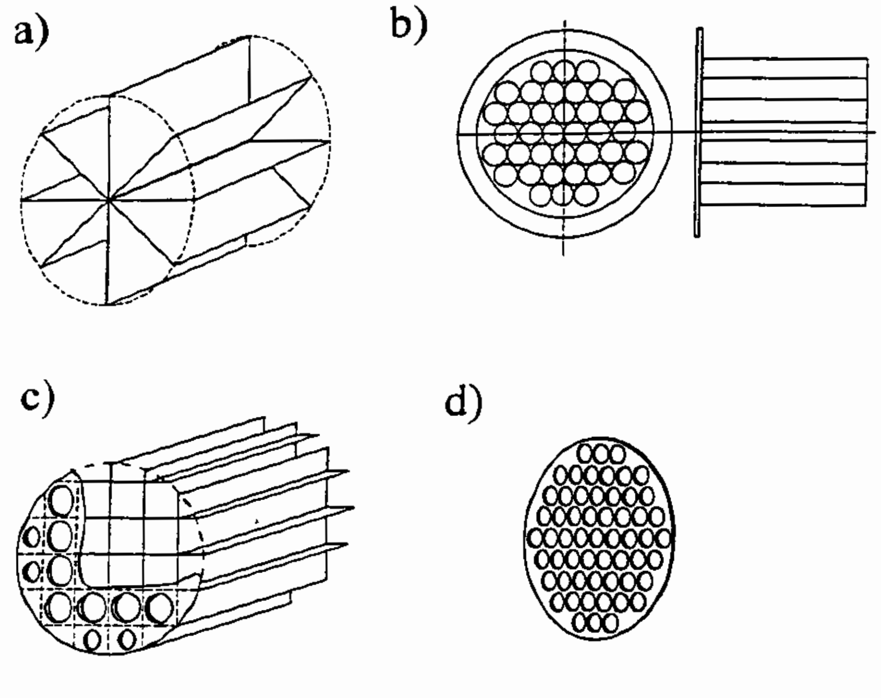


Fig. 9: Types of flow conditioners investigated
a) Etoile flow straightener
b) Tube-bundle flow straightener
c) Zanker flow conditioner
d) Single perforated plate

The following few examples are selected to discuss the most important results of the investigations. The experience gained in the experiments shows that the damping elements studied can be divided into two groups:

Flow straighteners

These devices are effective against the tangential velocity components in the flow and suppress the swirl in particular. The axial velocity components are nearly not affected "positively", in the majority of the investigations asymmetries and elevations of the profile are even intensified. Typical representatives of this group are the Etoile and the tube-bundle straighteners. Figure 10 shows the pipe configuration and the flow profiles of an Etoile straightener installed downstream of a double bend out of plane. The tangential velocity components are well removed, but the local minimum of the axial components is more strongly developed at the outlet of the straightener than at its inlet. The remaining error shift of the turbine meter installed downstream of this configuration still amounts + 0,28 % compared with meter's indication for the undisturbed flow. A very similar sitiuation can be observed when the Etoile is replaced by a tube-bundle straightener (see Figure 11).

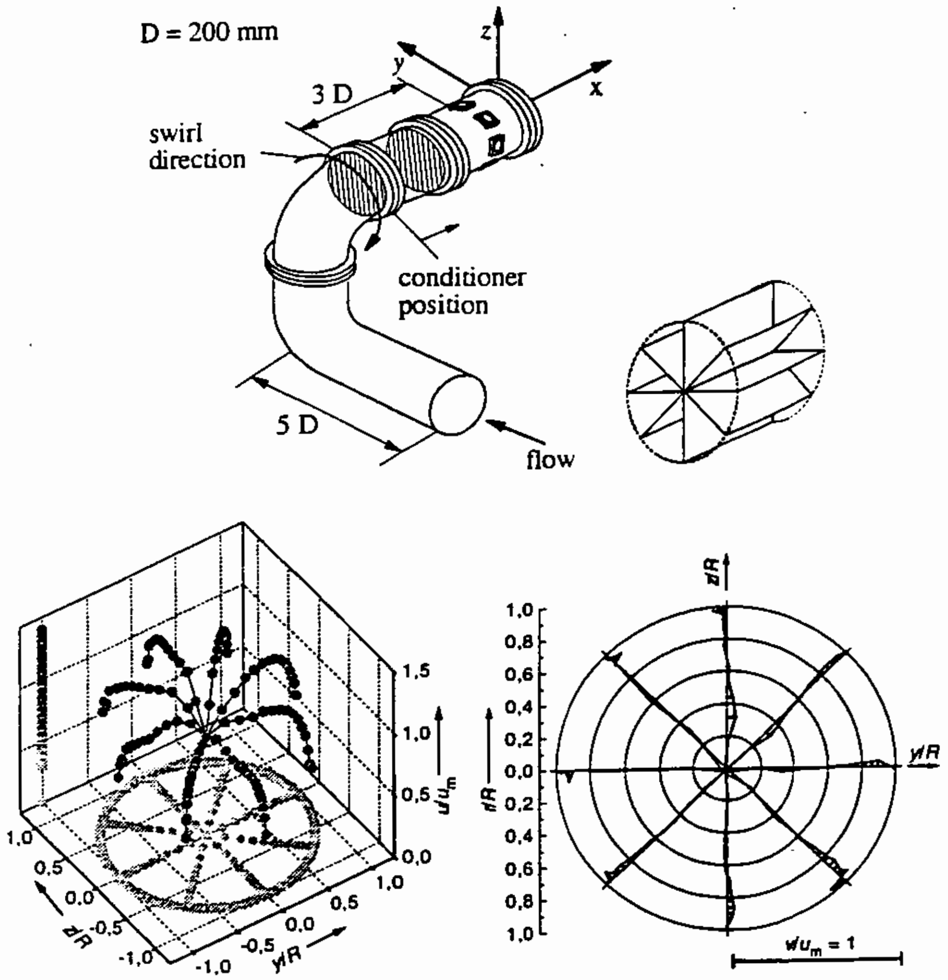


Fig.10: Schematic view of the pipe configuration investigated and perspective plot of the axial components u (left picture) and the tangential components v (right picture) of the velocity distributions downstream of a double bend out of plane with unchanged diameter and an Etoile straightener directly behind the perturbation

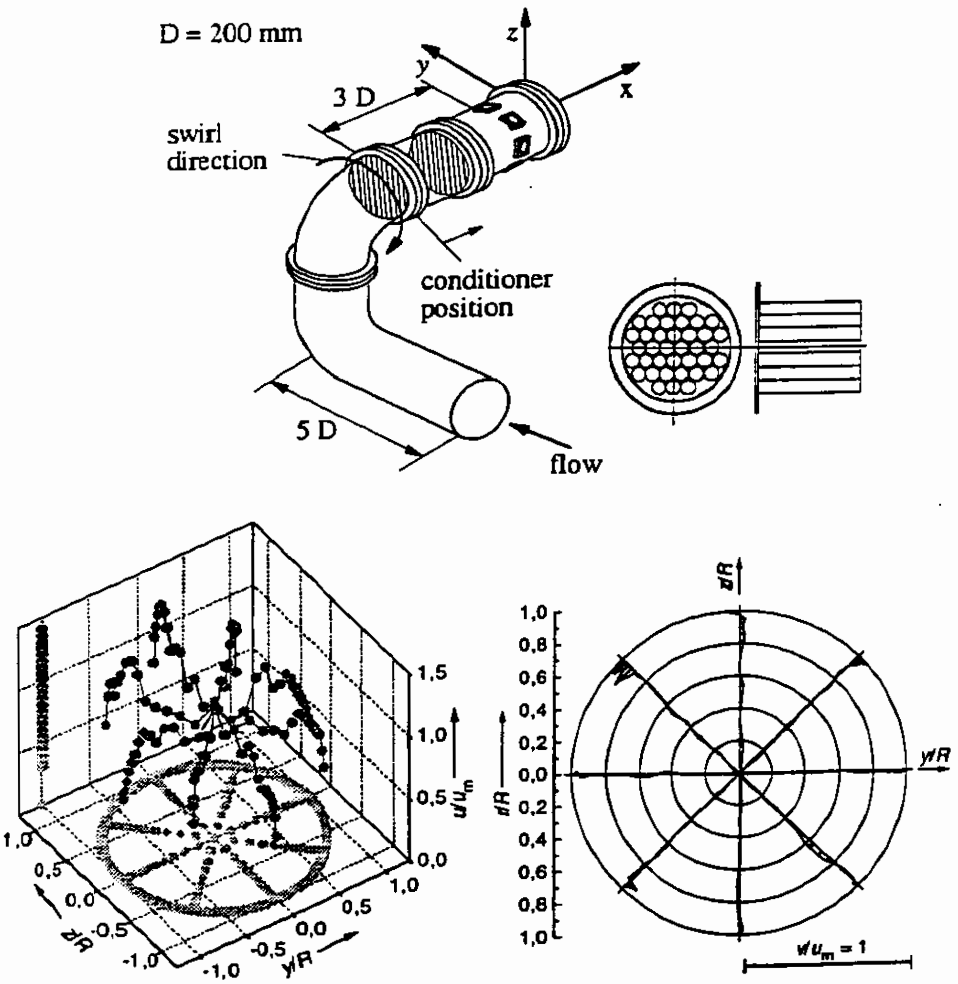


Fig. 11: Schematic view of the pipe configuration investigated and perspective plot of the axial components u (left picture) and the tangential components v (right picture) of the velocity distributions downstream of a double bend out of plane with unchanged diameter and a tube-bundle straightener directly behind the perturbation

Flow conditioners

Damping elements of the second type influence both the tangential and the axial velocity components of a disturbed flow. Zanker conditioners and perforated plates belong to this group. Figure 12 shows the axial and tangential velocity components of the flow downstream of a double bend out of plane and a Zanker conditioner. The velocity distribution obtained is very similar to that of an undisturbed flow. The remaining error shift of the turbine meter downstream of this configuration amounts to + 0,03 %, i.e. it lies clearly within the uncertainty of the flowrate standard (critical nozzles) used to investigate the meter behaviour.

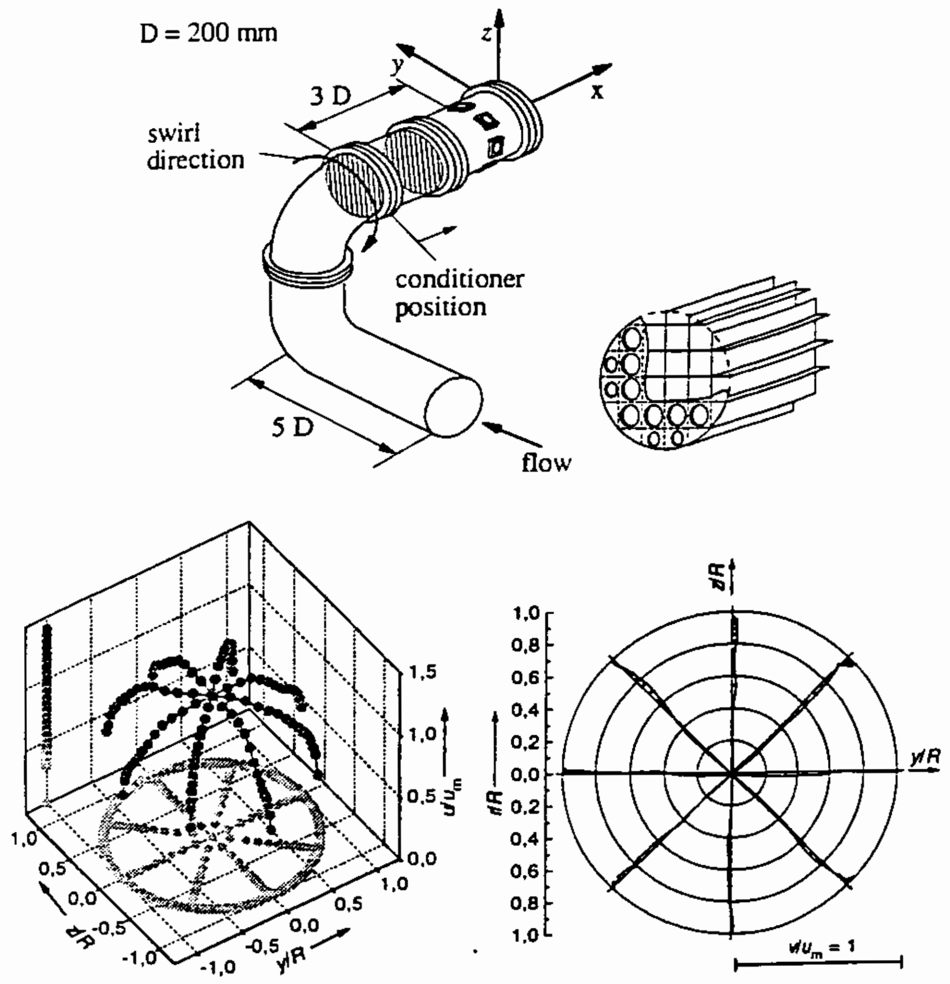


Fig. 12: Schematic view of the pipe configuration investigated and perspective plot of the axial components u (left picture) and the tangential components v (right picture) of the velocity distributions downstream of a double bend out of plane with unchanged diameter and a Zanker conditioner directly behind the perturbation

However, not only the type of the flow straightener/conditioner is of importance for reducing or removing flow disturbances downstream of unfavourable pipe geometries. The distance between the perturbation and the conditioner can also have a decisive influence on the result. This is why a lot of experiments were carried out to find the optimum geometrical arrangement of the various pipe and conditioner elements.

Figure 13 shows one example of such an investigation: A conventional perforated plate was installed directly downstream of a high level perturbation (Figure 13a) and 2 *D* behind the double bend's outlet (Figure 13b). The flow distributions were measured at a distance of 5 *D* downstream of the perturbation. The differences of both axial velocity distributions differ significantly. The 2 *D* distance between the plate and the perturbation shows a remarkable effect on the normalization of the axial velocity distribution, and this is confirmed by the error shifts of the turbine meter installed directly downstream of the configurations described: + 0,46 % for the configuration of Figure 13a) and + 0,12 % for the configuration of Figure 13b).

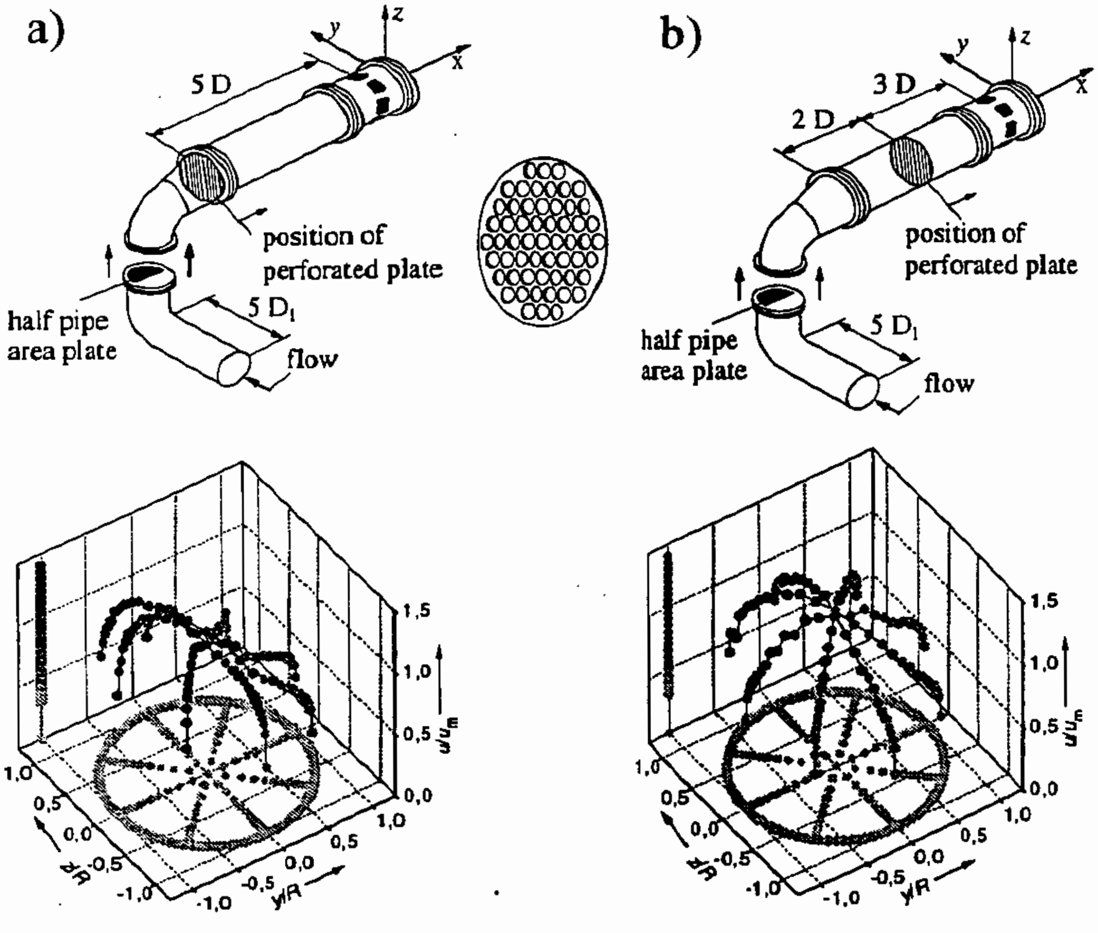


Fig. 13: Schematic view of the pipe configurations investigated and perspective plots of the respective axial components u of the velocity distributions downstream of a high level perturbation and a perforated plate
a) installed directly at the outlet of the double bend
b) installed at a position of 2 D behind the perturbation

More than 50 different conditioner configurations altogether were investigated and used to enlarge the existing flow profile catalogue. The results of these measurements allow well-aimed recommendations to be given for the use of optimum flow straightener/ conditioner configurations (if necessary, in combination with straight pipes of corresponding lengths), when the flow pattern downstream of a given pipe geometry is known.

5 CHARACTERIZATION OF DISTURBED FLOW PROFILES BY SPECIAL FLOW FIELD PARAMETERS

An analysis of the disturbed flow profiles investigated shows that there are three typical kinds of deviations of the profiles from the undisturbed case:

- *Swirl*

  This phenomenon can be described very easily looking at the tangential components of the velocity distributions (see, for example, Figures 6 and 7). Swirls are typical for all configurations with double bends out of plane. They can have a left-hand or a right-hand orientation in dependence on the position of the bends each to the other. Normally symmetrical configurations generate swirls of the same intensity, but with different directions of rotation. An example is shown in Figure 14.

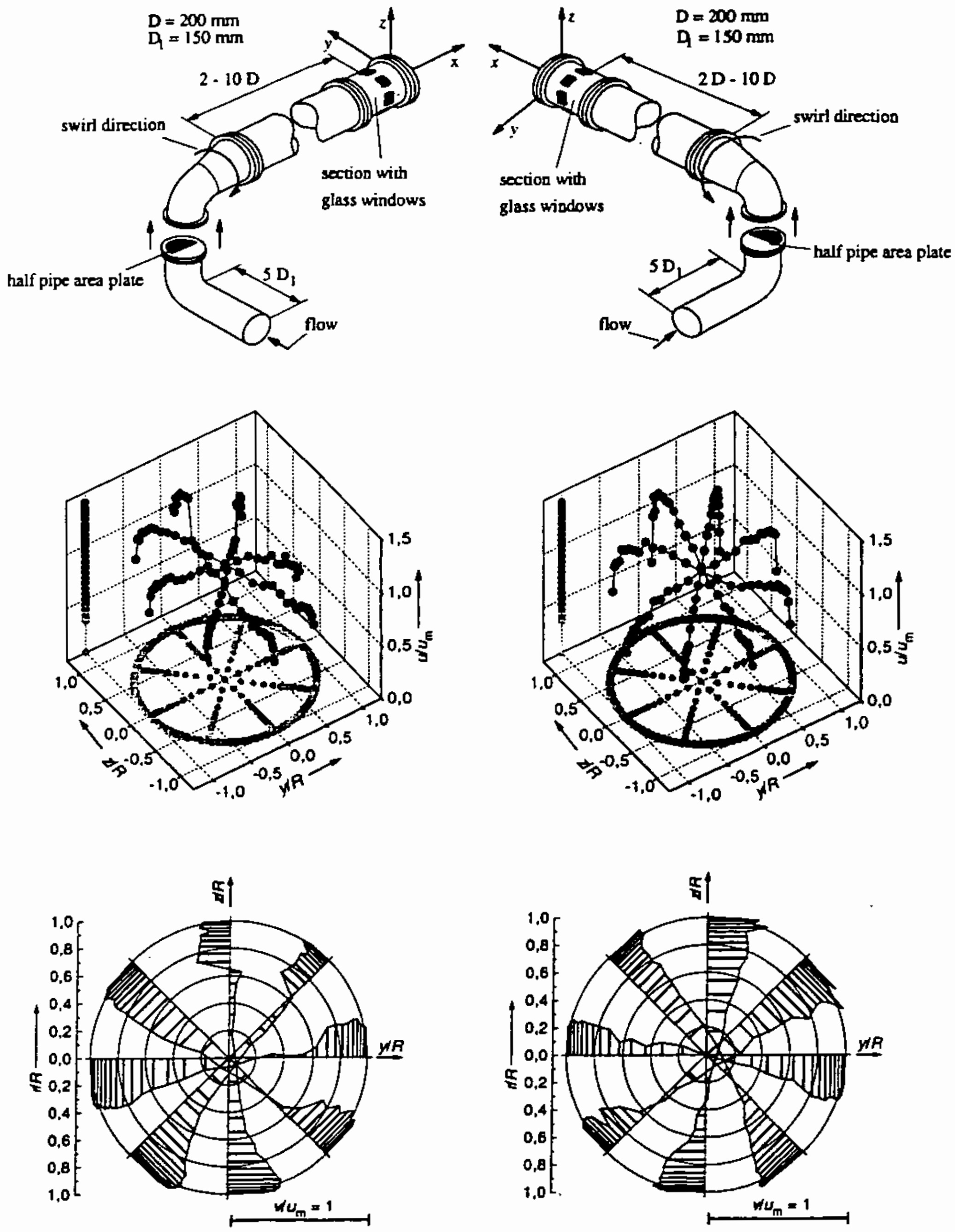


Fig. 14: *Schematic view of the pipe configurations investigated and perspective plots of the respective axial components u and tangential components v of the velocity distributions downstream of a high level perturbation with right-hand and left-hand swirl and a straight pipe of 2 D in length*

- *Asymmetry*

  If the distribution of the axial velocity component is not axisymmetric we speak about an asymmetry of the flow. Asymmetries can be observed downstream of any non-axisymmetric pipe configurations. Vivid examples for this kind of profil deformation are the axial velocity distributions in Figures 6a and 7a for the double bend configurations.

- *Flatness*

  Flatness is another kind of deformation of the axial velocity profil in a pipe flow. It characterizes (axisymmetric) deviations from the ideal shape of the axial flow profil. Respective examples are shown in Figure 5a (the single bend configuration) and Figure 10 (double bend configuration with Etoile flow straightener) where the velocity profiles have their maximum not at the centre of the pipe but an elevation towards the pipe wall.

To find out suitable parameters describing disturbed flow profiles, these three kinds of flow characteristics should be analyzed in relation to their effect on the flowmeter type to be investigated. According to the aims of the PTB project this analysis was started with turbine gas meters. Because turbine meters operate as integrators, the flow profile in front of the meter should be described by integrating flow field parameters.

Figure 15 shows the relations between the blades of a turbine wheel and the axial velocity of the gas flow.

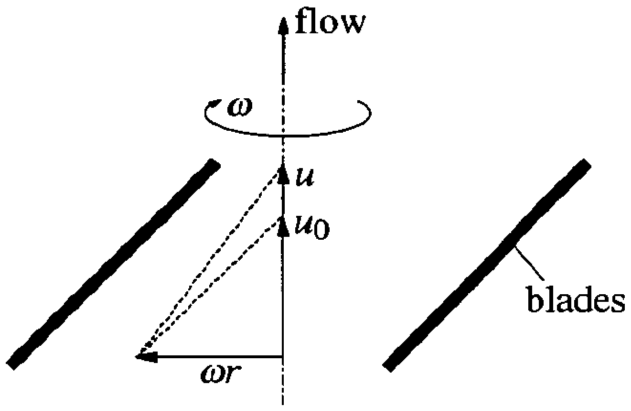


Fig. 15: Relations between the turbine wheel and the axial flow velocity u

In a coordinate system rotating with the blades, a certain axial velocity u_0 exists at which the flow is parallel to the blades. If the axial velocity is different, the flow will not be parallel to the blades and a force in the tangential direction will result, which is the first radial moment of the momentum flux. In the case of constant flowrate, at a specific rotating speed, the accelerating and decelerating forces at the turbine wheel are in balance. If the profile is changed (but not the flowrate), the force at the turbine wheel will also be changed and the wheel has to attain a different rotating speed before it comes to a new balance. Although the flowrate remains constant the rotating speed of the turbine wheel changes producing a change of the meter reading, e.g. an error shift. This interaction between flow and turbine wheel leads to the assumption that the integral of the first radial moment of axial momentum fluxes is an effective flow field parameter for comparing the error shift of a turbine meter with the profile disturbances upstream of the meter. The definition of the axial momentum number is:

$$K_u = \frac{\iint_A \rho \cdot u^2 \cdot r \cdot \mathrm{d}A}{\pi \cdot \rho \cdot u_m^2 \cdot R^3} \tag{4}$$

where u is the axial velocity, u_m is the bulk velocity, r is the radius coordinate, ρ is the gas density, A is the pipe cross-sectional area and R is the pipe radius.

A fully developed pipe flow has a certain momentum number K_{u0}. As only the difference between a disturbed flow and the undisturbed case is of interest, in the following the difference $\Delta K_u = K_u - K_{u0}$ will be used.

The same idea is also used to define the flow field parameter for the tangential velocity v. As shown in Figure 16, the gas flow with the axial velocity u is parallel to the wheel blades.

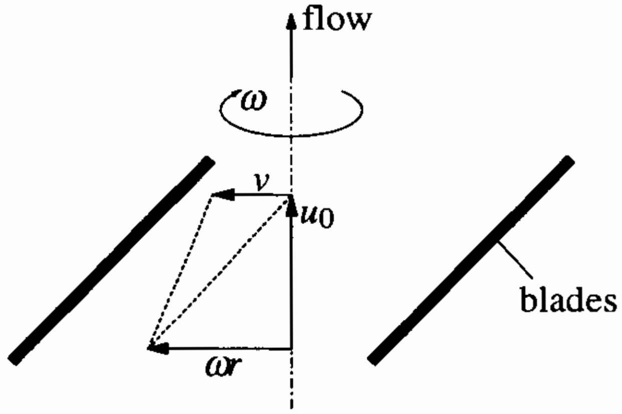


Fig. 16: Relations between the turbine wheel and the tangential flow velocity

If the flow contains an additional tangential component v, a force at the turbine wheel will again occur. The integrated first radial moment of tangential momentum fluxes, which is equal to the swirl number used by Kitoh [23] and Steenbergen [24] is therefore chosen to evaluate the force due to the tangential component. Following the considerations about K_u, the definition of the swirl number is:

$$K_v = \frac{\iint_A \rho \cdot u \cdot v \cdot r \cdot \mathrm{d}A}{\pi \cdot \rho \cdot u_m^2 \cdot R^3} \tag{5}$$

The sign of the swirl number is related to the rotating direction of the swirl. Right-hand swirls have positive, left-hand swirls negative numbers.

Asymmetry is the third significant characteristic of the flow profiles. The distance of the centroid of the mass flow from the pipe axis is used to describe this asymmetry (Figure 17).

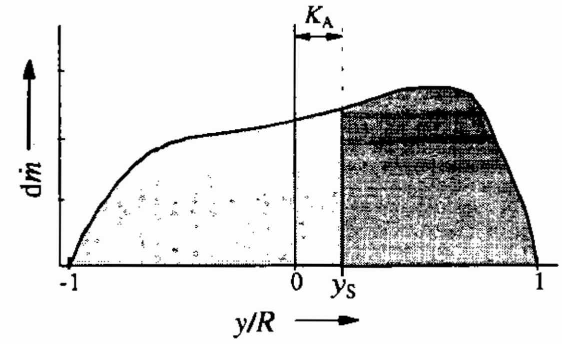


Fig. 17: Flow field parameter K_A for describing the asymmetry of the axial profile. K_A is the distance of the centroid (y_S) of the mass flow element $d\dot{m}$ from the pipe axis.

The respective flow field parameter - the non-dimensional asymmetry number K_A - is defined as follows:

$$K_A = \frac{\sqrt{\left(y_S^2 + z_S^2\right)}}{R}$$

$$y_S = \frac{\iint_A y \cdot d\dot{m}}{\dot{m}} \quad \text{and} \quad z_S = \frac{\iint_A z \cdot d\dot{m}}{\dot{m}} \tag{6}$$

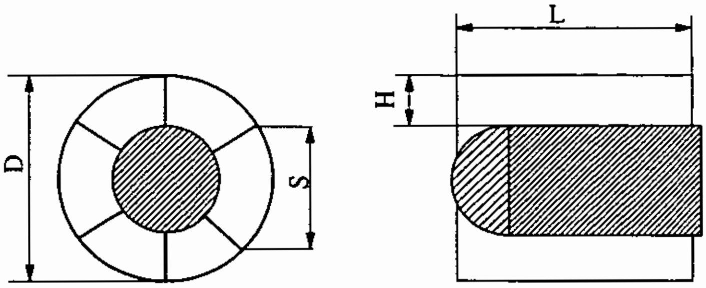
where y, z are the coordinates of the pipe cross-section, y_S, z_S are the coordinates of the centroid, A is the area of the pipe cross-section, $d\dot{m}$ is the mass flow through a differential cross-sectional area and $\dot{m}$ is the mass flow.

6 AN EMPIRICAL MODEL TO EXPLAIN THE ERROR SHIFT OF TURBINE METERS

After defining the flow field parameters and quantifying the disturbances of the flow profiles it is now possible to compare these disturbances with the shift of the calibration curves (error shift) of gas meters applied downstream of the pertubation. In the PTB project four turbine meters were used for this investigation. Two of them were of the same geometry, so three geometries were tested. Table 2 gives a survey of the main characteristics of these turbine meters.

If disturbed profiles propel a turbine meter, the resulting error shift depends on the geometry of the meter inlet. An extensive study of this dependence was performed by Dijstelbergen et al. [25]. This study shows that the same perturbation can lead to opposite results only due to a change in the meter geometry.

Table 2: Geometrical characteristics of the turbine meters tested



Turbine meter TM i	Number of vanes	D (mm)	S (mm)	H (mm)	L (mm)	Rotation of the turbine wheel
TM 1	6	200	104	45	90	right-turn
TM 2a and 2b	17	200	37	45	80-95	right-turn
TM 3	12	200	52	25	110	right-turn

The velocity profiles measured in front of the turbine meter have of course changed due to the inlet construction before the gas flow interacts with the turbine wheel. It is assumed that this change does not depend on the flowrate and can be described for every turbine meter by constant model parameters. This assumption and the sensitive comparison of the profile catalogue with the measured error shifts ΔE led to the simple model:

$$\Delta E_{\text{model}} = a_1 K_v (1 + a_2 K_A) + a_3 \Delta K_u \qquad (7)$$

The model parameters a_1 to a_3 are characteristic for every turbine meter, and they have to be determined by regression from the flow field parameters and error shifts. The results for the four meters tested are given in Table 3.

Table 3: Values of the model parameters a_1 to a_3 in eq. (7) for the turbine meters tested

Turbine meter	a_1	a_2	a_3
TM 1	4,8	7,9	6,6
TM 2a and 2b	2,2	-7,2	3,0
TM 3	-0,18	130	5

The model can be validated by plotting the predicted error shifts ΔE_{model} versus the measured ΔE_{meas}. If the model matches well with reality, all points should lie close to the diagonal axis $y=x$ as can be seen in Figures 18 to 20.

The error shifts shown in these following figures were measured

- at different flowrates (25% q_{max} up to q_{max} of the turbine meters)
- downstream of different pipe configurations (straight pipes with free inlet, single bends, double bends out of plane)
- at different distances between perturbation and turbine meter.

In most cases shown, the difference between the measured and the predicted error shifts is smaller than 0,15%. It has to be emphasised that only part of the measured error shifts were used to determine the model parameters a_1 to a_3 for turbine meters TM1 and TM 2a. In addition to this, the model parameters for the meter TM 2b were derived directly from those of meter TM 2a which is of identical geometry (Fig. 19).

The model also allowed the error shift to be sufficiently predicted when meter TM 2b was used at 0 D downstream of a double bend out of plane although the profiles for this configuration were not measured. The values of the flow field parameters for a position directly behind the double bend (0-D-distance) were extrapolated from the values at the distances 2 D, 5 D and 10 D between the perturbation and the measuring position.

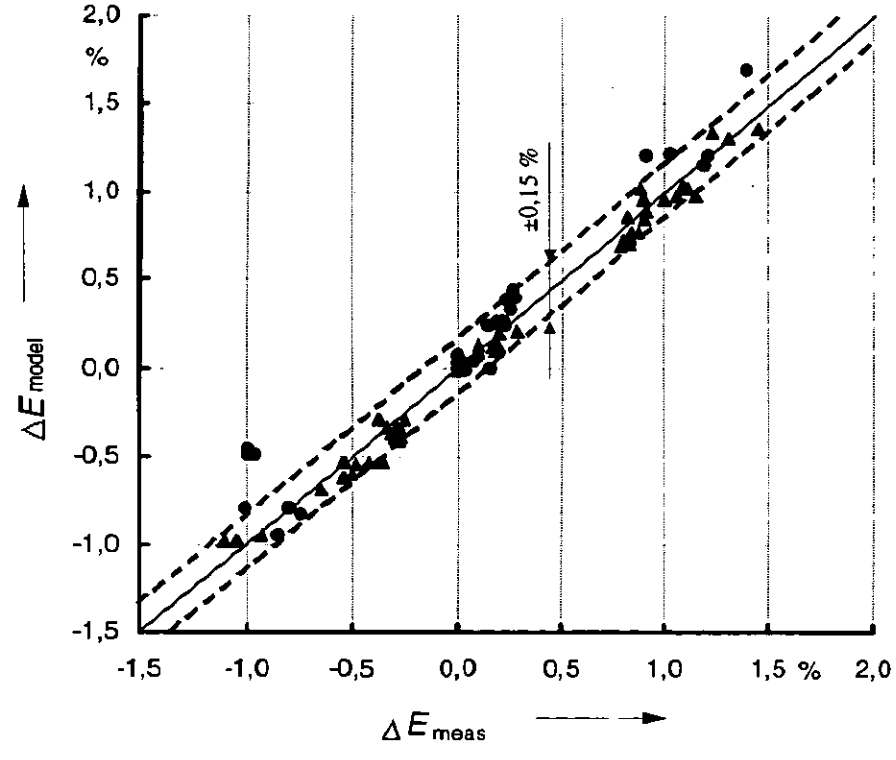


Fig. 18: Comparison of measured error shift ΔE_{meas} and predicted ΔE_{model} of turbine meter TM 1 according to eq. (7) and Table 3

▲ *measured results used for regression to determine the model parameters a_1 to a_3 in eq. (7)*

● *measured results not used for regression*

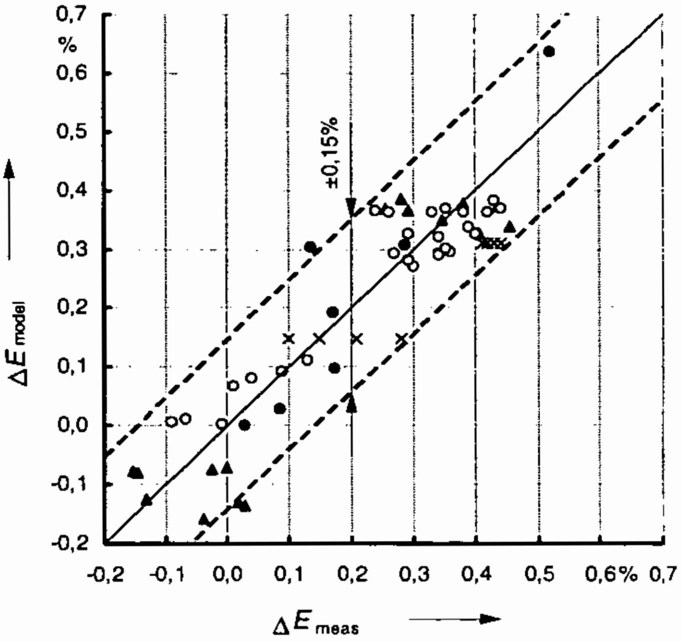


Fig. 19: Comparison between measured error shift ΔE_{meas} and predicted ΔE_{model} of turbine meters TM 2a and 2b according to eq. (7) and Table 3

- ▲ *results measured for TM 2a and used for regression to determine the model parameter a_1 to a_3 in eq. (7)*
- ● *results measured for TM 2a and not used for regression*
- ○ *results measured for TM 2b; the model parameters were taken directly from the meter TM 2a*
- × *results measured for TM 2b 0 D downstream of a double bend out of plane; the flow field parameters were extrapolated from the values at 2 D, 5 D, 10 D*

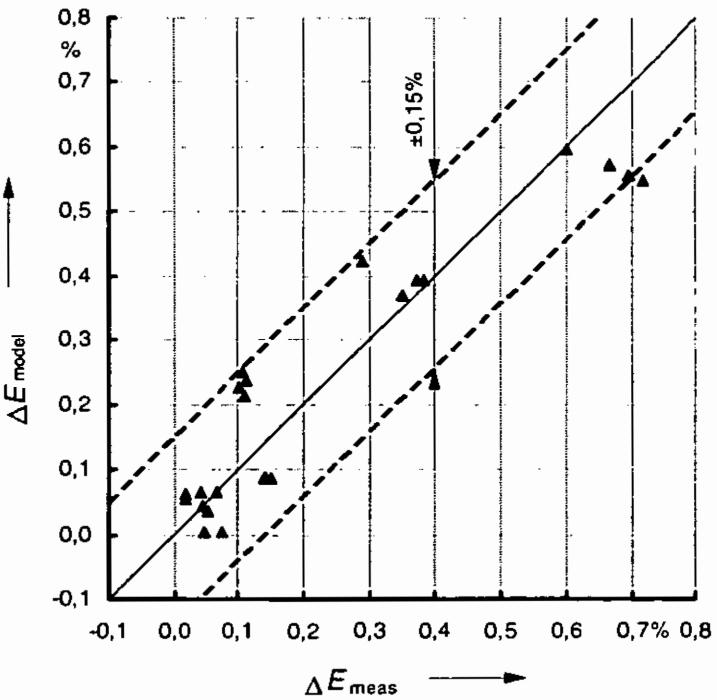


Fig. 20: Comparison between measured error shift ΔE_{meas} and predicted ΔE_{model} of turbine meter TM 3; according to eq. (7) and Table 3

When the uncertainty of 0,15% of the model is considered, the following points have to be kept in mind:

- The calibration curves of the turbine meters could be measured with an uncertainty of 0,08%; this is half the model uncertainty.
- The pipe configurations were used as recommended in the OIML R-32 [22]. That means that there is a *5D* straight pipe with free inlet upstream of the bends. The flow profile 5 *D* downstream of a free inlet depends on the conditions of the room, e.g. the distances from the pipe inlet to the ground or wall. Hence, the development downstream of the bends too, is not absolutely independent of the conditions of the test room and may differ in the different experimental setups.
- The accuracy of the numerical evaluation of the profiles is bounded by the limited number of measuring points.
- Sometimes there was a delay of several days between the measurements of the basic calibration curve and those of the calibration curve downstream of a special pipe configuration. A slight drift of the calibration curves between the measurements during this time cannot be excluded.

So it may be stated that the model is of sufficient quality to predict meter readings. It can explain the very different reaction of turbine meters to the same disturbed velocity profile and seperates the influence of flatness, swirl and asymmetry on the error shift. In addition, the model provides a new basis for evaluating the efficiency of flow conditioners. Both, the estimation of the error shift and the evaluation of flow conditioners, are of great interest and importance for practical use in industrial flow measurement as well as in flowmeter development and research.

7 REFERENCES

1 **Irving, S.J.:** The effects of bends on the discharge coefficient of orifice plates. In: Proceedings of the IMEKO-Conference on Flow Measurement of Fluids, FLOMEKO'78, Groningen, The Netherlands, Sept. 1978, 247-252

2 **Morrow, T.B.; Park, J.T.; McKee, R.J.:** Determination of installation effects for a 100 mm orifice meter using a sliding vane technique. J. Flow Meas. Instrum. **2** (1991), 14-20

3 **Morrison, G.L.; DeOtte, R.E. Jr.; Beam, E.J.:** Installation effects upon orifice flowmeters. J. Flow Meas. Instrum. **3** (1992), 89-94

4 **Mattingly, G.E.; Yeh, T.T.:** Elbow effects on pipe flow and selected flow meters. In: Proceedings of the 6th International Conference on Flow Measurement, FLOMEKO'93, Seoul, Korea, Oct. 1993, 61-79

5 **van der Kam, P.M.A.; van Dellen, K.:** The effect of double bends out of plane on turbine meters. J. Flow Meas. Instrum. **2** (1991), 61-68

6 **Halttunen, J.:** Installation effects on ultrasonic and electromagnetic flowmeters: a model-based approach. J. Flow Meas. Instrum. **1** (1990), 287-292

7 **Takamoto, M.; Utsumi, H.; Watanabe, N.; Terao, Y.:** Installation effects on vortex shedding flowmeters. J. Flow Meas. Instrum. **4** (1993), 277-285

8 **Brennan, J.A.; McFaddin, S.E.; Sindt, C.F.; Kothari, K.M.:** The influence of swirling flow on orifice and turbine flowmeter performance. J. Flow Meas. Instrum. **1** (1990), 5-8

9 **Heritage, J.E.:** The performance of transit time ultrasonic flowmeters under good and disturbed flow conditions. J. Flow Meas. Instrum. **1** (1990), 24-30

10 **Spearman, E.P.; Sattary, J.A.; Reader-Harris, M.J.:** Comparison of velocity profiles downstream of perforated plate flow conditioners. In: Proceedings of the 7th International Conference on Flow Measurement FLOMEKO'94, Glasgow, Scotland, June 1994

11 **Laws, E.M.; Ouazzane, A.K.:** A further study into the effect of length on the Zanker flow conditioner. J. Flow Meas. Instrum. **6** (1995), 217-224

12 **Laws, E.M.; Ouazzane, A.K.:** A preliminary study into the effect of length on the performance of the Etoile flow straightener. J. Flow Meas. Instrum. **6** (1995), 225-233

13 **Laws, E.M.; Ouazzane, A.K.:** A further study investigation into flow conditioner design yielding compact installations for orifice plate flow metering. J. Flow Meas. Instrum. **6** (1995), 187-199

14 **Stuart, J.W.; Park, J.T.; Morrow, T.B.:** Experimental results of an improved tube-bundle flow conditioner for orifice metering. In: Proceedings of the 7th International Conference on Flow Measurement FLOMEKO'94, Glasgow, Scotland, June 1994

15 **Harbrink, B.; Zirnig, W.; Hassenpflug, H.-U.; Kerber, W.; Zimmermann, H.:** The disturbance of flow through an orifice plate meter run by upstream header. In: VDI-Berichte 768, VDI-Verlag: Proceedings of the 5th International IMEKO-Conference on Flow Measurement FLOMEKO, Düsseldorf, Germany, Oct. 1989, 75-90

16 **Park, J.T.; Morrow, T.B.; Yeh, T.T.; Mattingly, G.E.:** Effect of velocity profile from tee and bundle flow conditioner on orifice meters. In: Proceedings of the International Gas Research Conference, Orlando, Florida, Vol. III, Nov. 1992, 223-234

17 **Wendt, G.; Kramer, R.; Dopheide, D.:** Einsatz eines miniaturisierten Laser-Doppler-Anemometers auf Halbleiterbasis für die Geschwindigkeitsprofilmessung in Gasleitungen. PTB-Mitt. **102**, 1992, 445-453

18 **Kramer, R.; Mickan, B.; Wendt, G.; Müller, H.; Dopheide, D.:** Automatisierte Messung von Strömungsprofilen im Einlauf von Gaszählern mit einem 2-Komponenten Halbleiter-LDA-System. In: Lasermethoden in der Strömungsmeßtechnik, 4. Fachtagung GALA e.V.; Verlag Shaker Aachen 1995, 31.1-31.6

19 **Schlüter, T.:** PIV-Messungen der Geschwindigkeitsverteilungen hinter verschiedenen Strömungsgleichrichtern (Dissertation). Shaker Verlag GmbH, Aachen 1996

20 **Sattary, J.A.; Reader-Harris, M.J.; Johnstone, L.A.:**
Computation of flow through bends. In: Proceedings of the 14th North Sea Flow Measurement Workshop, Peebles, Scotland, 28-31 October 1996

21 **Hilgenstock, A.; Ernst, R.:**
Analysis of installation effects by means of Computational Fluid Dynamics - CFD versus experiments? J. Flow Meas. Instrum. **7** (1996), 161-171

22 International Recommendation: Rotary piston gas meters and turbine gas meters. (OIML R-32); Edition 1989 (E)

23 **Kitoh, O.:** Experimental study of turbulent swirling flow in a straight pipe. In: Journal Fluid Mechanics **225** (1991), 445-479

24 **Morrow, T.B.; Park, J.T.; McKee, R.J.:** Determination of installation effects for a 100 mm orifice meter using a sliding vane technique. In: Flow Meas. Instr. **2** (1991)

25 **Dijstelbergen, H.H.; Bergervoet, J.T.M.:** Optimal straightening vanes for turbine meters. In: Proceeding of the 3rd International Symposium on Fluid Flow Measurement 1995, March 19-22, 1995; San Antonio, Texas