„Guidelines for the Fluid Mechanical Validation of Calibration Test-Benches in the Framework of EN 1434“

- October 2009 -

Contents:

1. Aims and methods

- The current EN 1434-2006 Standard [EN1434] contains for the first time specifications on the velocity characteristics of calibration test-benches for heat meter flow sensors (DFS).
- Part 4, section 6.22 of the Standard stipulates that the velocity distribution of the test-bench used for the calibration of flow sensors is to be fully developed and undisturbed, i.e. rotation symmetric and free from swirl.
- Furthermore tests of flow sensors in relation to their performance under disturbed flow conditions („Flow Disturbances“) for type approval or for conformity assessment are prescribed.
- The following serve as guidelines for providing metrological evidence of the abovementioned requirements (validation) and for the general assessment of the velocity distribution in the piping of calibration test-benches.
- After determination of the flow conditions in the piping, the results are characterised and quantified by means of performance indicators. Subsequently the determined values of the performance indicators are compared with specified criteria based on analytical expressions for developed velocity distributions.

- If conformity of the stipulated velocity distributions according to these guidelines is accomplished, a report containing the methods and conditions of measurement as well as the results of the measurements will be accepted by the national metrology institutes in Germany, Austria, Switzerland and other notified bodies.
- Fulfilment of the validation procedure depends on the measured results and their evaluation by the notified body.

2. Validation Specifications

2. 1 Measuring procedure

- A contactless method for measuring velocity distributions is preferred.
- The use of optical methods for measurement is recommended.
- Contactless laser doppler velocimetry (LDV) is ideal for this purpose since it provides meaningful results with low measurement uncertainties for reasonable device und time expenditures.

2.2 Measuring conditions

a) Test-bench under consideration:

- Test-benches used exclusively for calibration of flow sensors in production (production test-benches) are distinguished from those used for conformity assessment and in development projects (accreditation test-benches).
- The implementation of the guidelines is obligatory in Switzerland for operators of all accreditation test-benches of flow sensors used for conformity / accreditation purposes.
- The implementation of the guidelines is likewise obligatory in Switzerland for operators of all production test-benches used for calibrating flow sensors.
- Test-bench operators are for example manufacturers of flow sensors, district heating suppliers, independent test and repair services and authorities.

- The national metrology institutes or notified bodies determine for each individual operator which test-benches are to be validated. Criteria for the choice are for example the type and number (serial calibration) of flow sensors to be calibrated, the operating conditions and the hydraulic complexity of the test-benches (in particular the flow generating method).

b) Validation and revalidation of test-benches:

- Validation is part of the conformity assessment process.
- Revalidation is necessary for any modifications made to the test-bench which affect the velocity distributions in the test section (e.g. modification of inflow, flow generating system or meter clamping mechanism).
- Revalidation is to be carried out according to the criteria for the conformity assessment process.

c) Parameters for the measurements:

- Measurement quantities:
  - The axial velocity and related degree of turbulence of the primary flow are the quantities to be measured.
  - Additionally, the tangential velocity as a measure for the degree of swirl in the flow, or the complete secondary flow is to be determined.
  - Recommendations:
    - During the measurements the reference flow rate and the fluid temperature should be recorded at intervals with a time resolution of at least 60 seconds.
    - In addition, the stability of the flow should be controlled by LDV measurements at a chosen point in the flow cross-section (e.g. middle of pipe) for at least 60 minutes.
- Measuring point:
  - The measurements are to be made at the position of the first flow sensor in the measuring section independent of whether the test-bench is used for single or serial calibrations.
  - In the case of inadequate flow distributions at the measuring position of the first flow sensor, the measuring point is to be moved and/or appropriate flow conditioners are to be installed.
- Pipe diameter at the measuring point:
  - The pipe diameter at the measuring point must correspond to that of the feed pipe to the measuring section (i.e. without reductions or enlargements) or to that of the meter clamping device or to that of the flow conditioner.
  - If the pipe diameters of the flow sensors to be calibrated are smaller than that of the feed pipe to the measuring section, then the pipe diameter at the measuring point is to be chosen as the largest of the pipe diameters of the flow sensors to be calibrated.
  - Alternatively, individual specifications are obtainable from national metrology institutes or notified bodies.
- Measuring section requirements:
  - To avoid additional turbulence, smooth and gapless transitions between the measuring section pipe and the pipe at the measuring point must be assured. The maximum misalignment between the two pipes may not exceed five percent relative to the inner diameter of the measuring section pipe.
- Test flow rates:
  - The flow rates corresponding to q_i, $0.1 \cdot q_p$ and q_p of the chosen pipe size and of the largest flow rate range of the flow sensors to be calibrated are to be taken as the test flow rates.
  - Only measurements at q_p are necessary for swirl.
  - The fluid temperature must correspond to the calibration temperature (15 ± 5 °C or 50 ± 5 °C or 85 ± 5 °C).
  - To avoid additional effects due to stratified temperature distributions, the measurements should be carried out at fluid temperatures of 20 ± 5 °C for laminar flow conditions.
  - The water pressure should correspond to the operating conditions of the test-bench.
- Further conditions:
  - For selectable methods of flow generation for the test-bench (e.g. by means of elevated tanks or pumps), pumps are to be chosen.
  - In case fittings exist in the inlet pipe (e.g. temperature sensors extending into the flow) under operating conditions, measurements are to be made with these in place. For comparison, further measurements at q_p are to be made with the fittings removed.

- ∗ If there is a 90° bend in the feed pipe upstream of the measuring section, measurements of swirl profiles are to be made preferably in a plane at right angles to the plane of the bend or within at most ±45° to it.

d) Resolution and measurement uncertainty

- o Number of measuring points across the pipe cross-section:
  - ∗ Measurement of the axial velocity:
    - ♦ Profile data are to be collected for at least ten equally spaced diameters across the pipe cross-section (i.e. at most at 18° intervals), each diameter containing at least 20 points.
    - ♦ The profile should include points at the pipe centre (r/R = 0) and near to the representative distance from the pipe wall at which the local velocity corresponds to the bulk flow velocity.
    - ♦ For laminar flow the representative distance from the pipe wall is found at r/R = 0.707. For turbulent flow it is recommended to use the simplified AICHELEN point at r/R = 0.762.
  - ∗ Measuring the tangential velocity:
    - ♦ A least one profile with more than 20 points along a diameter is to be recorded.
- o Measurement uncertainty:
  - ∗ A maximum measurement uncertainty of 5% (corresponding to twice the standard deviation) is to be attained for the determination of local velocities (including uncertainties in the determination of the measuring positions).

2.3 Presentation and analysis of the measured results

- The report to be submitted to the notified body must contain the relevant information under the following headings:
  - o Short description of the test-bench or corresponding documentation of the plant as an appendix
  - o Documentation of the installation conditions of the inlet and outlet sides of the test-bench
  - o Description of the method of measurement and set-up for the flow diagnostics
  - o Explanation of the measurement technique (regime and conditions)
  - o Graphical presentation of the results
  - o Calculation of the performance indicators (see Section 3 and Appendix 1)
  - o Summary.

2.4 Acceptance of the results

- The reliability of the flow conditions is assessed by the notified bodies or national metrology institutes.
- Quantification and comparison of the results is achieved with the performance indicators, namely profile factor, asymmetry factor, turbulence factor and the maximum swirl angle.
- As guidance to the permissibility of the results, the following ranges or maximum values of the performance indicators should not be exceeded:

o Profile factor K_p:	Range	$0.8 \leq K_p \leq 1.3$
o Asymmetry factor K_a in %:	maximum value	$K_{a.max} = 1\ \%$
o Turbulence factor K_{tu}:	maximum value	$K_{tu.max} = 2$
o Swirl angle in degrees:	maximum value	$\Phi_{max} = 2°$

- The notified body makes the final decision of whether the conditions for the required undisturbed and fully developed flow have been met, even though the results may lie within the limits of the abovementioned ranges or values.

3. Performance indicators

3.1 Introduction

- The assessment of the pipe velocity is evaluated by means of performance indicators which allow fast and easy conclusions to be drawn about the flow. They are also manageable for the practitioner and can find applications in related fields.
- YEH and MATTINGLY [Yeh94, Yeh95] have defined such performance indicators in connection with studies on installation effects on different volumetric flow meters by means of LDV. These have been used as basis in the following treatment.
- Generally the performance indicators can be split into three groups [Mick95]:
    - Performance indicators which are determined from point measurements of velocity
    - Form parameters which are based on the integration of the differences in the velocity profile referred to either a point measurement of velocity or a characteristic velocity, or
    - Performance indicators which describe the velocity distribution in the general integral form

      $$K = \iint \overline{w} \cdot^{l} \overline{v} \cdot^{m} r \cdot^{n} dr \; d\varphi$$

      where w … is the axial velocity

      and v … the tangential velocity

      which, depending on the values of the exponents l, m and n, possess different physical meanings.
- Based on the capabilities of current LDV measuring systems, performance indicators from the second and third groups should be used if possible.
- The performance indicators are preferably based on fully developed flow conditions.
- Tolerance ranges to determine adequate developed flow conditions are to be defined which again should preferably have relationships with currently available recommendations and which reflect practical realities of calibration test-benches (e.g. no „laboratory" flows).

3.2. Axial Velocity (w)

- To be assessed are:
    - The profile form, i.e. a flattening, dipping or peaking of the profile compared to fully developed flow => profile factor,
    - asymmetry in the velocity distribution, i.e. for example a displacement of the centroid from the pipe centreline => asymmetry factor and
    - the maximum degree of turbulence in a given region (e.g. core region) of flow as a measure of fluctuations in velocity or perturbations in flow => turbulence factor.

a) Profile factor

- The definition follows in accordance with the determination of P_5 by YEH and MATTINGLY [Yeh94]:

$$K_p = \frac{K_{p.meas}}{K_{p.s}}$$

where K_p … is the profile factor,

$K_{p.meas}$ … profile index of the measured profile,

and $K_{p.s}$ … profile index of the standard profile:

$$K_{p.meas} = \frac{\int (w_m - w) \cdot dr}{w_{vol} \cdot D} = \frac{1}{2 \cdot w_{vol}} \int_{-1}^{1} (w_m - w) \cdot d\left(\frac{r}{R}\right)$$

$$K_{p.s} = \frac{\int (w_{s.m} - w_s) \cdot dr}{w_{vol} \cdot D} = \frac{1}{2 \cdot w_{vol}} \int_{-1}^{1} (w_{s.m} - w_s) \cdot d\left(\frac{r}{R}\right)$$

where w_m … is the measured velocity at the pipe centreline (r/R = 0)
w … the measured local velocity at r/R
w_{vol} … the bulk flow velocity $w_{vol} = Q/(\pi \cdot R^2)$
R … the pipe radius
r … the local measuring position
w_s … the local velocity of the standard profile
$w_{s,m}$ … the velocity at the pipe centreline (r/R = 0) of the standard profile

- The profile factor K_p is a measure of the peakness ($K_p > 1$) or flatness ($K_p < 1$) of the measured profile in comparison to the standard profile.
- The profile index of the measured profile $K_{p.meas}$ is to be normalised by the fully developed laminar or turbulent velocity standard distributions ($K_{p.s}$).
- The value of the profile factor is therefore "1" for fully developed flow.

- Fully developed laminar flow (standard laminar profile) can be determined with the HAGEN-POISEUILLE equation (see Fig.1):

$$\frac{w(r/R)}{w_{vol}} = 2 \cdot \left[1 - \left(\frac{r}{R}\right)^2\right]$$

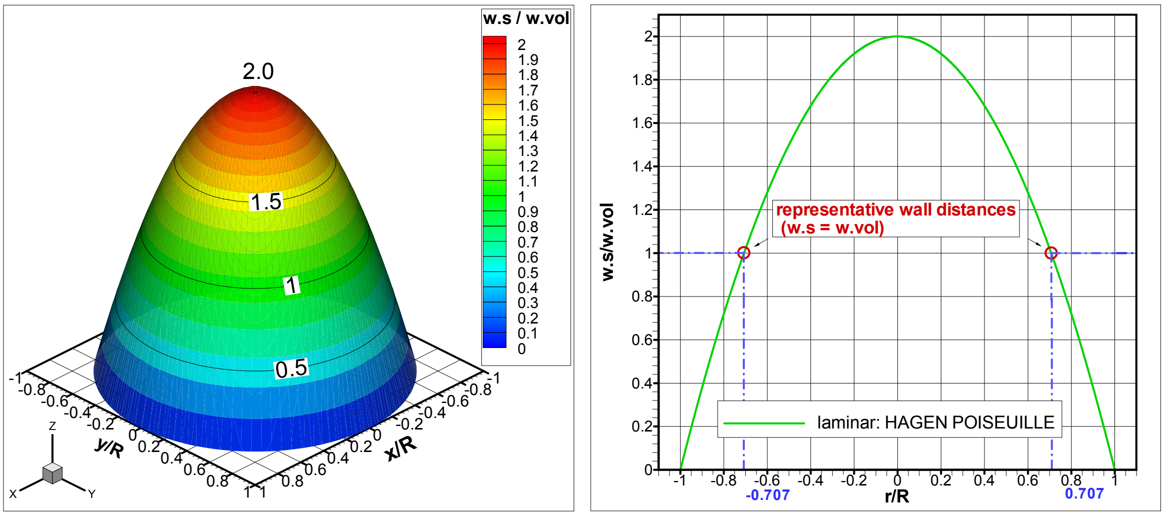

Fig. 1: Standard laminar profile after HAGEN POISEUILLE

- Fully developed turbulent flow (standard turbulent profile) can be described by various equations (e.g. power law, logarithmic law, piecewise description and correction functions).
- For the present case the equation of GERSTEN & HERWIG [Ger92, Ger04], which is a closed formulation of the velocity distribution at wall and core layers, has been chosen (see Fig. 2).
- Reasons for this choice are:
    - Reflects current technical stand with reference to experimental data (see „Superpipe" experiment from CALTECH Princeton => [McKeon et al 04])
    - Possibility to update easily through modification of the constants
    - Closed analytical expression of the flow profile with wall and core zones
    - No discontinuities at the pipe centre.
- The equations and constants for a hydraulically smooth pipe in the range 4000 < Re < 300000 according to GERSTEN & HERWIG [Ger04] are as follows:

$$\frac{w(r/R)}{w_{vol}} = \frac{2 \cdot \mathrm{Re}_\tau}{\mathrm{Re}} \cdot Z$$

where $\mathrm{Re} = \frac{D \cdot w_{vol}}{\nu}$ and $\mathrm{Re}_\tau = \frac{R \cdot w_\tau}{\nu}$

w_τ being the wall shear stress velocity

$$Z = \frac{1}{\Lambda}\left[\frac{1}{3} \cdot \ln\left(\frac{\Lambda \cdot y^+ + 1}{\sqrt{(\Lambda \cdot y^+)^2 - \Lambda \cdot y^+ + 1}}\right) + \frac{1}{\sqrt{3}}\left(\arctan\frac{2 \cdot \Lambda \cdot y^+ - 1}{\sqrt{3}} + \frac{\pi}{6}\right)\right] + \frac{1}{4 \cdot \kappa}\ln\left(1 + \kappa \cdot B \cdot (y^+)^4\right)$$
$$- \frac{\alpha}{2 \cdot \kappa \cdot a}\ln\left(1 + a \cdot \left(\frac{r}{R}\right)^2\right) + \frac{1}{\kappa}\ln\left(1 + \left|\frac{r}{R}\right|\right) - \frac{\beta}{2 \cdot \kappa \cdot b}\ln\left(1 + b \cdot \left(\frac{r}{R}\right)^2\right) + C_2$$

$$y^+\left(\mathrm{Re}_\tau, \left(\frac{r}{R}\right)\right) = y \cdot \frac{w_\tau}{\nu} = \frac{w_\tau}{\nu} \cdot R \cdot \left(1 - \left|\frac{r}{R}\right|\right) = \mathrm{Re}_\tau \cdot \left(1 - \left|\frac{r}{R}\right|\right)$$

Iterative determination of Re_τ :

$$\frac{1}{2} \cdot \mathrm{Re} = \mathrm{Re}_\tau \cdot \left(\frac{1}{\kappa} \cdot \ln \mathrm{Re}_\tau + C_1 + C_2 + C_3\right)$$

$\kappa = 0.421$
$A = 6 \cdot 10^{-4}$
$B = 0.0011$
$C_2 = 1.23$
$\Lambda = 0.119$
$a = -0.2714$
$b = 5.567$
$\alpha = -0.1656$
$\beta = 7.735$

and

$C_1 = 5.60$
$C_3 = -4.28$
für $\mathrm{Re} < 3 \cdot 10^5$:
$C_3 = -4.28 - \frac{201}{\mathrm{Re}_\tau}$
$C_1 + C_2 + C_3 = 2.55 - \frac{201}{\mathrm{Re}_\tau}$

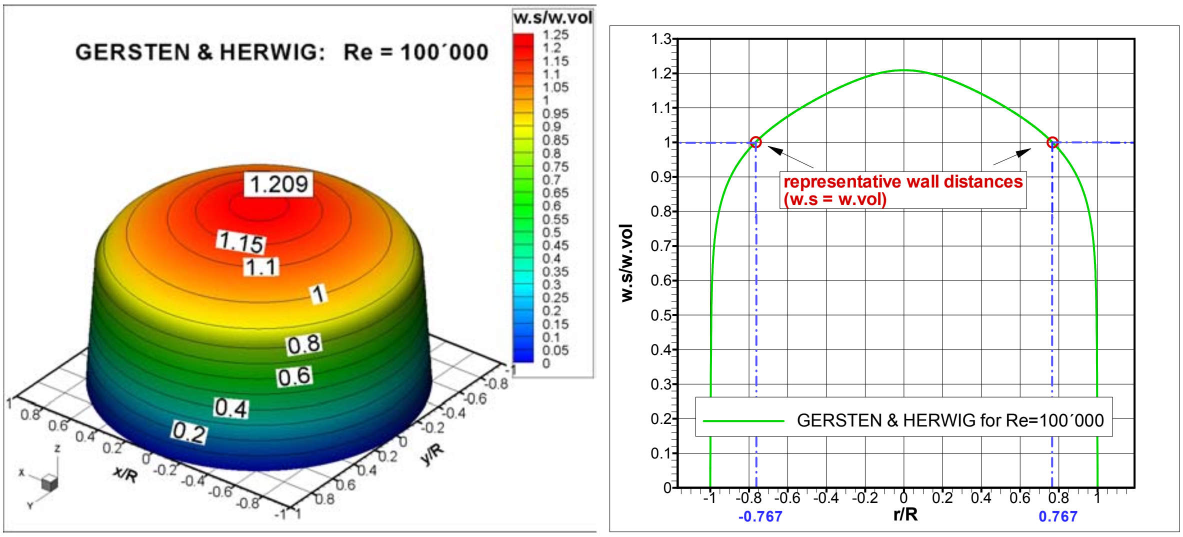

Fig. 2: Standard turbulent profile after GERSTEN & HERWIG (at Re = 100000)

- Fig. 3 illustrates graphically the interpretation of the profile factor.

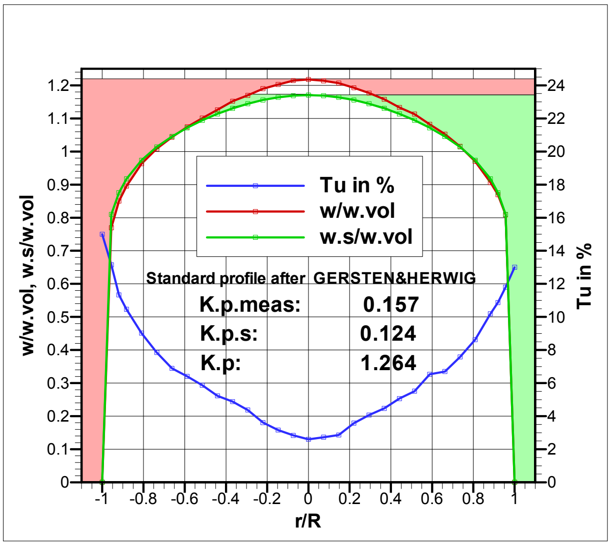

Fig. 3: Graphical interpretation of the profile factor

(red area [half of the profile partially hidden on the right] = $\int_{-1}^{1} (w_m - w) \cdot d\left(\frac{r}{R}\right)$,

green area [half of the profile also partially hidden on the left] = $\int_{-1}^{1} (w_{s.m} - w_s) \cdot d\left(\frac{r}{R}\right)$)

b) Asymmetry factor

- The definition follows in accordance with the determination of D_{10} by YEH and MATTINGLY [Yeh94]:

$$K_a = \frac{\int r \cdot w^m \cdot r^n \cdot dr}{D \int w^m \cdot r^n \cdot dr} = \frac{\int r \cdot w^1 \cdot r^0 \cdot dr}{D \int w^1 \cdot r^0 \cdot dr} = \frac{\int_{-1}^{1} \left(\frac{r}{R}\right) \cdot w \cdot d\left(\frac{r}{R}\right)}{2 \cdot \int_{-1}^{1} w \cdot d\left(\frac{r}{R}\right)}$$

where m = 1, n = 0, with values in %

- The asymmetry factor quantifies the average flow displacement from the pipe centre.
- Fig. 4 illustrates graphically the asymmetry factor.

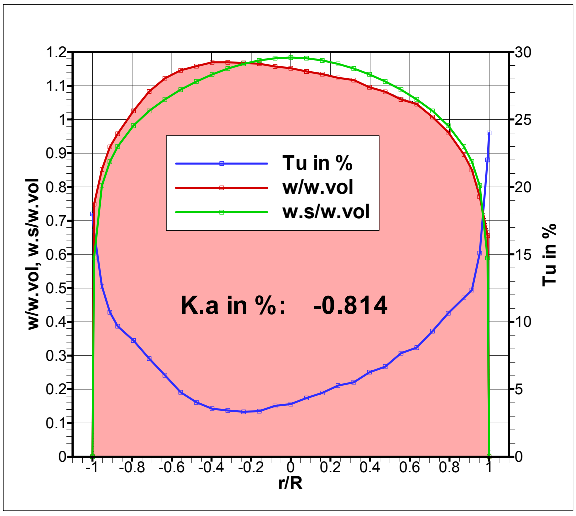

Fig. 4: Example of the asymmetry factor

c) Turbulence factor

- Turbulence in flow is a measure of the temporal fluctuations in velocity about the time-averaged mean, i. e. of the „perturbations“ in such flows (Fig. 5).

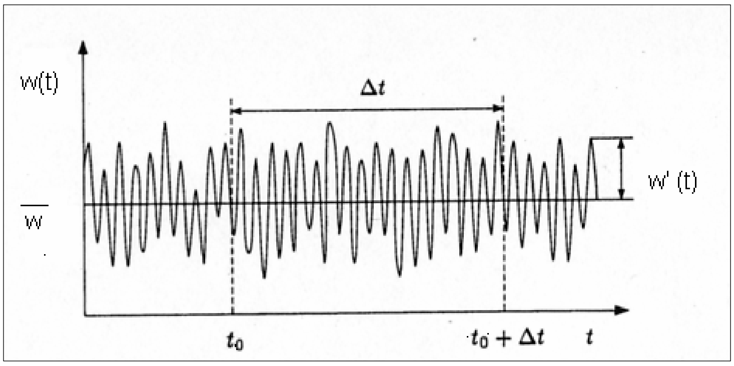

Fig. 5: Velocity spectrum ($\overline{w}$ … time-averaged mean velocity, w' (t)…velocity magnitude at time t)

- Experimentally, the description of turbulence is achieved with the aid of the degree of turbulence. By considering a one dimensional flow state, the following applies:

$$Tu = \frac{s_w}{\overline{w}} = \frac{\sqrt{\overline{w'^2}}}{\overline{w}}$$

where Tu … is the degree of turbulence in %,

w' … the magnitude of the axial velocity fluctuations,

$\overline{w}$ … the time-averaged mean of the axial velocity,

and s_w the standard deviation of the axial velocity

- The turbulence factor is defined as the ratio of the degree of turbulence in the core region of the flow $-0.2 \leq r/R \leq 0.2$ to that at the pipe centre of the standard profile:

$$K_{tu} = \frac{Tu_{max}\Big|_{r/R=\ 0.2}^{r/R=-0.2}}{Tu_s}$$

where Tu_{max} … is the maximum degree of turbulence in the core region

and $Tu_{,s}$ .. the degree of turbulence at the centre of the developed flow.

- DURST et al [Dur98] give the following relationship for the degree of turbulence at the centre of a developed channel flow for $Re_m \geq 4500$:

$$Tu_m = \frac{w'_m}{w_m} \cong 0.13 \cdot Re_m^{-\frac{1}{8}}$$

where $Re_m = \frac{D \cdot w_m}{\nu} = Re \cdot \left(\frac{w_m}{w_{vol}}\right)$

w'_m is the axial fluctuating velocity at the pipe centre,

and w_m the axial velocity at the pipe centre

- PASHTRAPANSKA [Pas04] has shown that this relationship is applicable to pipe flows to a very good approximation.
- The degree of turbulence at the centre of a developed pipe flow can therefore be approximated by the following expression:

$$Tu_s = 0.13 \cdot \left[Re \cdot \left(\frac{w_m}{w_{vol}}\right)_s\right]^{-\frac{1}{8}}$$

where $\left(\frac{w_m}{w_{vol}}\right)_s$ … is the velocity ratio of the standard profile.

- Fig. 6 depicts a measured profile of the degree of turbulence with numerical examples for the turbulence factor.

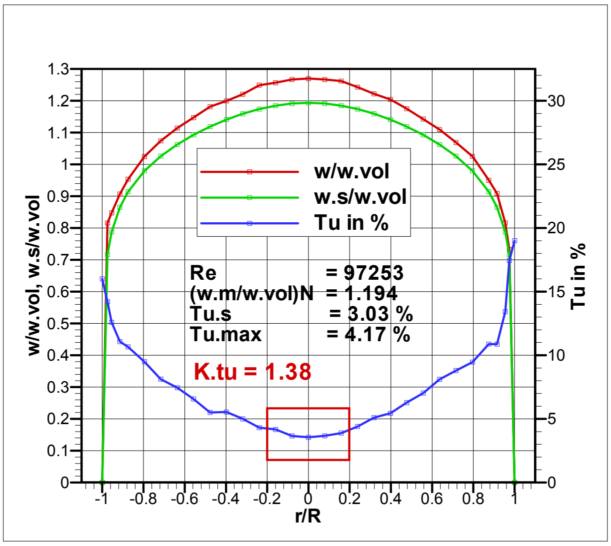

Fig. 6: Example of the turbulence factor

3.3. Tangential velocity component (v)

- The swirl angle or maximum swirl angle [Yeh95] can be used as a simple means for quantifying swirl in a flow:

$$\phi = \arctan(v / w_{vol})$$

where v is the tangential velocity (circumferential velocity)

$$\phi_{max} = \arctan(|v|_{max} / w_{vol})$$

- As depicted in Fig. 7, the swirl angle can be understood as the deviation of the flow vector from the ideal axial flow direction.

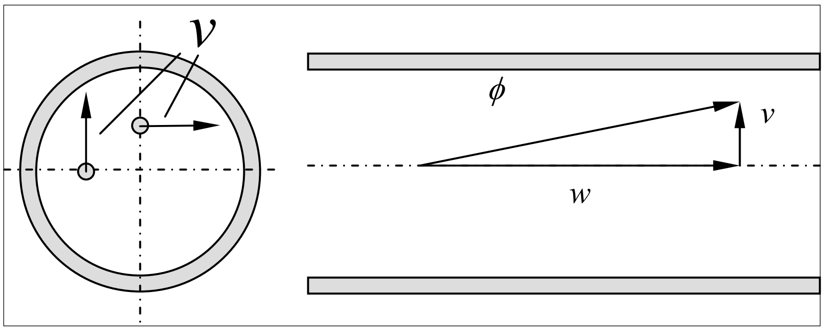

Fig. 7: Graphical interpretation of the swirl angle (v…tangential velocity (circumferential velocity), w…axial velocity, ϕ …swirl angle)

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Appendix: Example of the analysis of measured results by means of performance indicators

Measurement setup:
- DN 20, pipe inner diameter D = 19.8 mm
- Nominal volumetric flow Q = 500 l/h, water temperature T_w = 50 °C, water pressure p_w = 7.2 bar
- REYNOLDS number Re = 16205
- Measurements made at 15D downstream from a MITSUBISHI flow conditioning unit.

Results:
- Axial velocities and degree of turbulence:
  - LDV measurements in a flow cross-section containing 281 measuring points with 2000 measurements per point.
- Tangential velocities:
  - LDV measurements along a diameter (90° to both planes of a 90° out-of-plane double bend placed at the beginning of the measurement section) consisting of 50 measuring points with 2000 measurements per point.

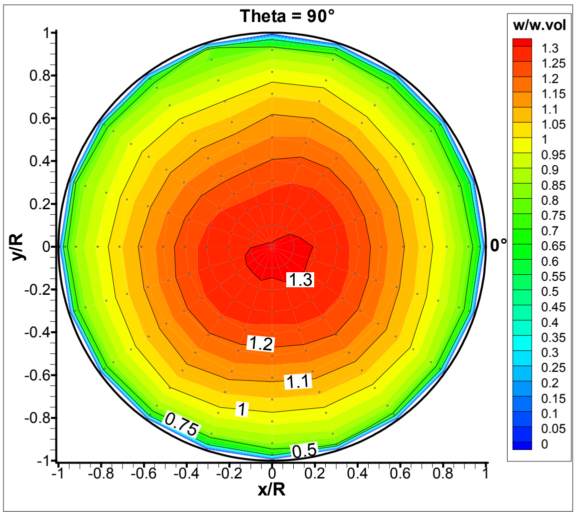

Fig. A1: 2D representation of axial velocity distribution

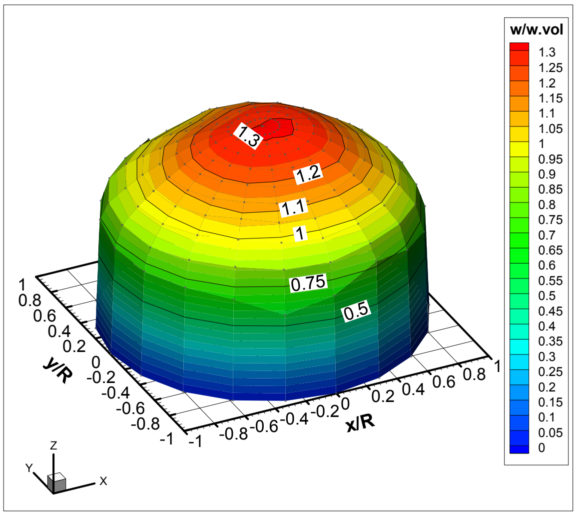

Fig. A2 3D representation of axial velocity distribution

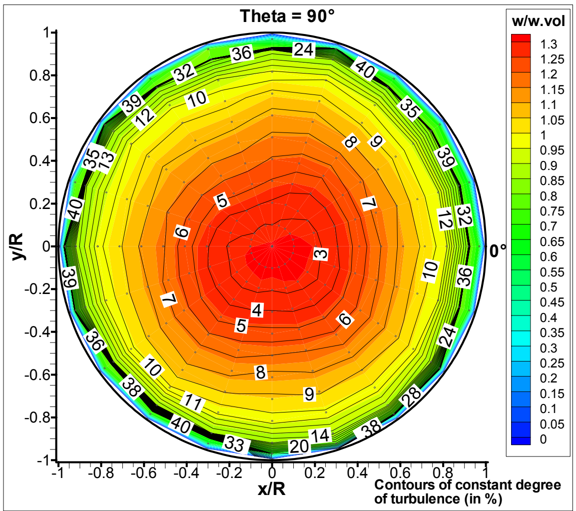

Fig. A3: Degree of turbulence distribution (to Tu_{max} = 40 %)

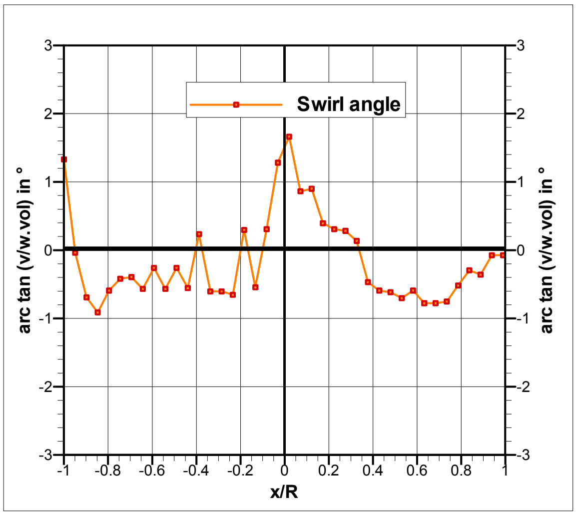

Fig. A4: Tangential velocity profile along a diameter

Table A1: Table of results of the calculation of performance indicators

Q in l/h:		497.00		$w_{s.m}/w_{vol}$:		1.280
w_{vol} in m/s:		0.4576		w_m/w_{vol}:		1.303
T_w in °C:		50		$w_m/w_{s.m}$ in %:		1.80
p_w in bar:		7.2		$K_{p.s}$:		0.181
Re:		16'217		Tu_s in %:		3.75
Theta		$w_{a.l}/w_{s.a}$ in %	$w_{a.r}/w_{s.a}$ in %	K_p	K_a in %	(K_{tu})*
Full profile	0	-2.45	-1.35	1.032	0.16	0.68
	18	-2.75	-1.06	1.044	0.29	0.67
	36	-3.50	0.52	1.024	0.37	0.70
	54	-2.49	2.34	1.004	0.40	0.70
	72	-0.44	0.28	1.028	0.03	0.74
	90	-1.19	-0.80	1.070	0.28	0.80
	108	-5.00	0.37	1.056	0.57	0.78
	126	-3.50	0.99	1.043	0.56	0.79
	144	-2.31	1.02	1.029	0.32	0.79
	162	-2.90	-1.89	1.054	0.05	0.73
Min. value		-5.00	-1.89	1.004	0.03	0.67
Max. value		-0.44	2.34	1.070	0.57	0.80
Max. lvaluel		5.00	2.34	1.070	0.57	0.80
Ø*				1.038		0.74
u = 2s in %				3.67		13.53
* arithmetic					* in the range -0.2 ≤ r/R ≤ 0.2	

In addition to the defined performance indicators, Table A1 also contains the ratio of measured velocities to standard profile velocities at the pipe centre ($w_m/w_{s.m}$) as well as ratios of measured velocities at representative distances from the pipe wall (simplified here by using the AICHELEN point at r/R = 0.762) of each left and right half of the profile to the corresponding velocities of the standard profile ($w_{a.l}/w_{s.a}$ und $w_{a.r}/w_{s.a}$).

Examples of measured velocity profiles:

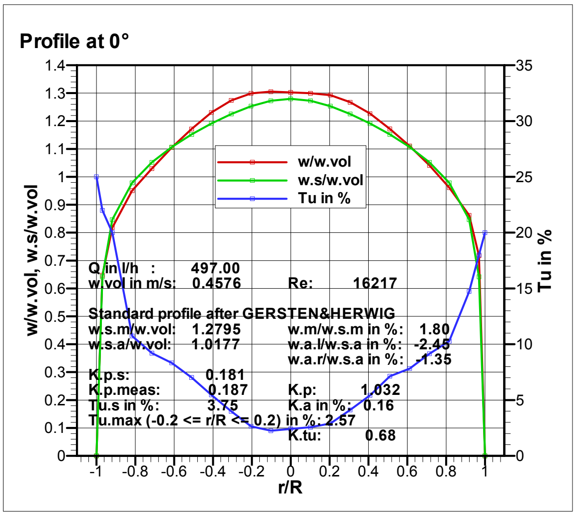

Fig. A5: Single profile at Theta = 0° (see Fig. A1)

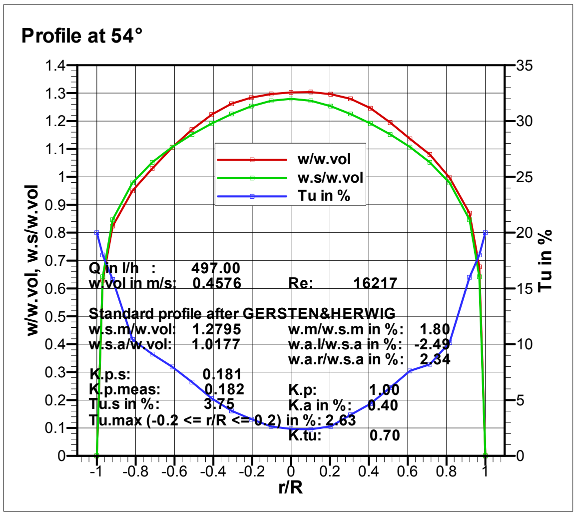

Fig. A6: Single profile at Theta = 54

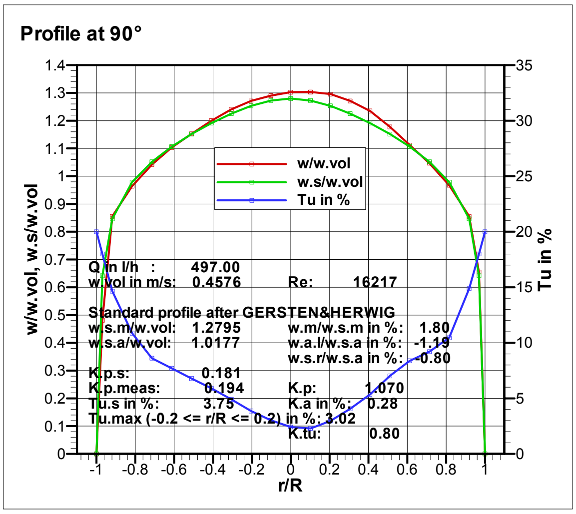

Fig. A7: Single profile at Theta = 90°

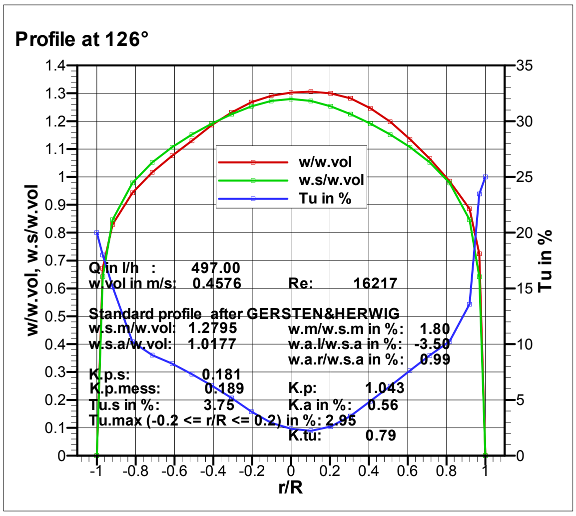

Fig. A8: Single profile at Theta = 126°

Nomenklatur:

D	Pipe inner diameter
K_a	Asymmetry factor
K_p	Profile factor
$K_{p.meas}$	Profile index of the measured profile
$K_{p.s}$	Profile index of the standard profile
K_{tu}	Turbulence factor
p_w	Water pressure
Q	Volumetric flow rate
q_p	Rated volumetric flow rate (p…permanent)
q_i	Minimum volumetric flow rate (i…inferior)
R	Pipe inner radius
r	local pipe inner radius
Re	REYNOLDS number
T_w	Water temperature
Theta	Angle of a diametral plane to the positive x-axis
Tu	Measured degree of turbulence of the axial velocity
Tu_s	Degree of turbulence of the standard profile at the pipe centre (r/R = 0)
Tu_{max}	Maximum measured degree of turbulence in the flow core region $-0.2 \leq r/R \leq 0.2$
v	Measured tangential velocity (circumferential velocity)
w	Measured local axial velocity
$w_{a.l}$	Measured axial velocity at a distance from the pipe wall at which $w = w_{vol}$ of the left half of the profile
$w_{a.r}$	Measured axial velocity at a distance from the pipe wall at which $w = w_{vol}$ of the right half of the profile
w_m	Measured axial velocity at the pipe centre (r/R = 0)
w_s	Local axial velocity of the standard profile
$w_{s.a}$	Axial velocity of the standard profile at a distance from the pipe wall at which $w = w_{vol}$
$w_{s.m}$	Axial velocity of the standard profile at the pipe centre (r/R = 0)
w_{vol}	Bulk flow velocity
x	Local position in the x direction
y	Local position in the y direction
ϕ	Swirl angle
ν	Kinematic viscosity
LDV	Laser Doppler Velocimetry / Anemometry
DFS	Flow sensor