FIELD AND LABORATORY EXPERIENCE WITH A CLAMP-ON ACOUSTIC TRANSIT TIME FLOW METER

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ABSTRACT

The paper discusses the results of laboratory and field measurements with a commercial type clamp-on acoustic transit time (CATT) flow meter.

Experience was gained on the one hand with systematic tests in the laboratory, with and without disturbed flow conditions at various installation positions with varying measurement setups. The flow rate measurements in the lab were carried out at steel pipes with internal diameter in the range of 13 to 502 mm. On the other hand field tests with the CATT flow meter were executed in the hydro power plant (HPP) Sassello on each of the thick-walled injector pipes of the horizontal two nozzle Pelton turbine. The resulting flow rates were compared to the discharge data deduced from the thermodynamic efficiency measurement.

The measurement uncertainty of CATT flow rates depends on the pipe diameter, the sensor selection and the magnitude of the average velocity of the fluid. For accurate flow rate measurements with CATT devices a minimum average velocity of 1 m/s should be exceeded. An accuracy of 2 to 5 percent was only achievable when respecting the minimum velocity condition. The influence of incorrect parameter settings on the total measurement uncertainty was analysed as well. Out of the multitude of measurements a table for best installation arrangement under varying measurement situations with disturbed or undisturbed flow conditions was developed. The gained experiences was compared to literature data or manufacturer specifications.

From the laboratory tests, as well as from the field tests at the HPP Sassello can be concluded that the repeatability is smaller than 0.4 percent. Such a repeatability is sufficient to carry out index efficiency testing in HPPs. CATT flow meters can also be used to check the efficiency curve shape when performing absolute efficiency measurements with a primary method. In such a measurement campaign CATT devices are well suited for cooling water and leakage flow rate measurements. However absolute efficiency measurements or even comparative tests before and after a turbine rehabilitation are not possible, because the measurement uncertainty is too high and reproducibility too low.

1. INTRODUCTION

Clamp-on acoustic transit time (CATT) flow rate metering is a method for non-invasive and non-intrusive flow rate measurement. The exterior installation avoids pressure losses, flow disturbances and can be installed quickly and without operation interruption. An accurate transducer positioning and the use of a couplant lube is crucial.

Essential for reliable measuring results is also that the boundary conditions given in the specifications concerning upstream and downstrean flow disturbances are respected.

Goal of the performed measurements was to determine the uncertainty under various test conditions. In order to determine the repeatability, specially defined repeatability measurements were carried out. Reproducibility tests were performed by dismantling and remounting the device in between each measurement. All measurements were repeated a few times to reduce the random uncertainty.

2. PHYSICAL PRINCIPLES OF CLAMP-ON ACOUSTIC MEASUREMENT DEVICES

2.1. Physical principle of the CATT measurement method

A CATT flow meter comprises three basic components: the transducers with the connection cables, the clamping arrangement and the signal processing unit. Flow rate measurements at pipes within the diameter range between 10 to 2000 mm is only possible with different transducer pairs. The used CATT device manufactured by Flexim includes three transducers (FSS, FSQ and FSM). Figure 1 gives for each transducer pair the specified application range.

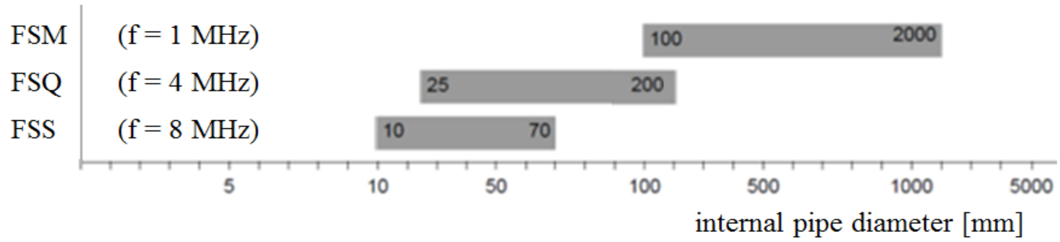

Fig. 1: Specified application range of the three transducer pairs

Each of these transducer pairs has its own defined frequency between 1 and 8 MHz. The FSS transducer for small pipes has a higher frequency (8 MHz) than the FSQ (4 MHZ) or the FSM (1 MHz), which are developed for pipes up to 2000 mm. High frequency signals have small wave lengths and lead to a better temporal resolution, which is important for CATT flow rate measurements at small pipes. Particles or bubbles in the flow, thick pipe walls or diffusion can lead to signal damping. Signals with low frequencies like 1 MHz are less influenced by damping.

Three different types of CATT arrangements are generally used for measurements:

- Direct through type, without any wall reflections (Fig. 2)
- Reflection type, with varying numbers of acoustic wall reflections (N) from 1 to 5 (Fig. 3)
- Cross-path type, without any wall reflections but with 2 pairs of transducers and coplanar crossed paths (Fig. 4)

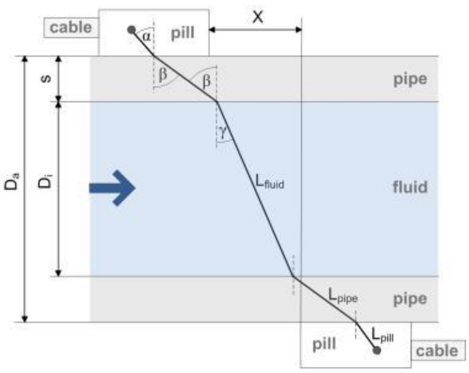

Fig. 2: Direct through CATT method (N=0)

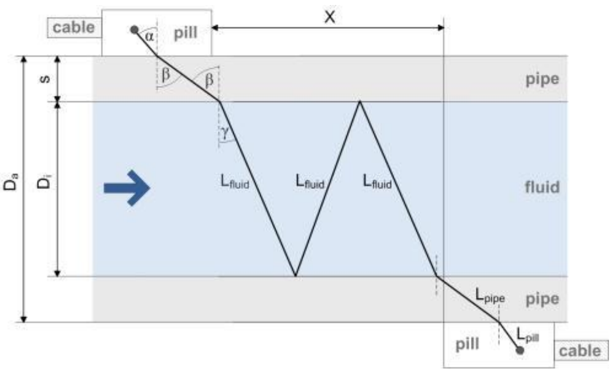

Fig. 3: Reflection CATT method (N=2)

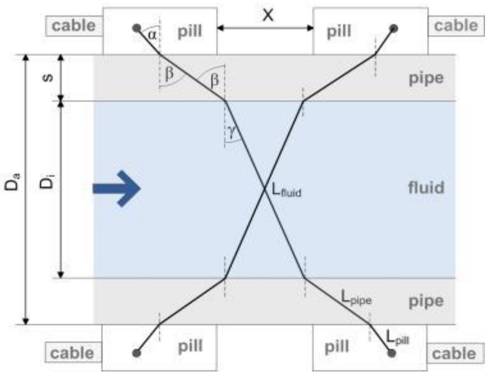

Fig. 4: Cross-path CATT method (N=0)

The piezoelectric oscillators inside the transducers emit acoustic wave bursts through the pipe wall and the fluid towards the other transducer. This process is alternating up- and downstream with respect to the flow direction. The signal processing unit measures the transit time difference between the up- and the downstream acoustic wave. With the measured transit time difference and the known geometry conditions the line average velocity of the fluid, over CATT path, can be calculated as

$$\bar{v} = \frac{L_{\text{fluid}} \cdot (N+1)}{2 \cdot \sin(\gamma)} \cdot \frac{\Delta t}{t_{fluid\_u} \cdot t_{fluid\_d}} \qquad (1)$$

where

$\bar{v}$	line average velocity along the acoustic path [m/s];
L_{fluid}	path length of the acoustic wave in fluid from wall to wall [m];
N	number of acoustic wall reflections [-];
γ	angle of the acoustic path in fluid [°] (cf. Fig. 2 – 4);
Δt	measured transit time difference [s];
t_{fluid_u}	transit time of the upstream acoustic wave in fluid [s];
t_{fluid_d}	transit time of the downstream acoustic wave in fluid [s].

The line average velocity along the acoustic path is corrected by the flow profile correction factor to get the average velocity over the entire cross-sectional area in the pipe. The flow profile correction factor can be computed with eq. (2) for smooth wall profiles measured by Nikuradse

$$K = 1.119 - 0.011 \cdot \log(\mathrm{Re}) \quad (2)$$

for the applicable Reynolds number (Re) range $3 \cdot 10^3 \leq \mathrm{Re} \leq 10^6$ with turbulent flow conditions, where

K	flow profile correction factor [s];
Re	Reynolds number [-].

The CATT flow rate results from the product of the flow profile correction factor, the line average velocity and the cross-sectional area with

$$Q = K \cdot \bar{v} \cdot A = K \cdot \frac{\bar{v} \cdot D_i^2 \cdot \pi}{4} \quad (3)$$

where

Q	CATT flow rate [l/s];
A	cross-sectional area in the pipe [m^2];
D_i	internal pipe diameter [m].

With the measured outer diameter and wall thickness, the internal pipe diameter is computed

$$D_i = D_a - 2 \cdot s \quad (4)$$

where

D_a	outer pipe diameter [m];
s	pipe wall thickness [m].

With the internal diameter and the angle of the acoustic path in fluid, the path length of the acoustic wave in fluid can be calculated as

$$L_{fluid} = \frac{D_i}{\cos(\gamma)} \quad (5)$$

Snell's law describes the relationship between the refraction and the angles of incidence, if acoustic waves passing through a boundary between two different medium. After formula transformation it is possible to calculate the angle of incidence in the fluid with

$$\gamma = \arcsin\left(\frac{\sin(\alpha) \cdot c_{fluid}}{c_{pill}}\right) \quad (6)$$

where

α	angle of incidence of the transducer [°];

c_{fluid} speed of sound in fluid [m/s];

c_{pill} speed of sound in pill material [m/s].

The speed of sound in fluid eq. (7) is a function of the compression modulus and the density, which vary as a function of temperature, pressure and the fluid type:

$$c_{fluid} = \sqrt{\frac{\kappa}{\rho}} \quad (7)$$

where

κ compression modulus [Pa];

ρ density [kg/m^3].

It is not permissible to neglect the variation of pressure and temperature. Our investigation was restricted to water as fluid. The speed of sound in water was approximated with formula (8) given by del Grosso [4]

$$c_{water} = 1402.39 + 0.156 \cdot p + 5.011 \cdot \vartheta - 0.05509 \cdot \vartheta^2 + 0.0002215 \cdot \vartheta^3 \quad (8)$$

where

c_{water} speed of sound in water [m/s];

p relative static pressure in the pipe [bar];

ϑ water temperature [°C].

The formula is applicable in the range of 0 – 50 bar relative pressure and in the range of temperatures of 2 – 40 °C.

The part of the pill, through which the acoustic wave travels, consists of ceramic material. For solids the speed of sound can be calculated with eq. (9).

$$c_{pill} = \sqrt{\frac{G}{\rho}} \quad (9)$$

where

G shear modulus [Pa].

The influence of temperature and pressure on the speed of sound in the pill is negligible.

The transit times in the pill and the pipe walls are constant as well as the trigger delays at transit times of the electrical signal in the cable. For evaluation of the up- or downstream transit times in the fluid these time delays plus the measured total transit time in up- or downstream direction are needed.

$$t_{fluid\_u} = \mathrm{t_u} - 2\left(t_{cable} + t_{pill} + t_{pipe}\right) \quad (10)$$

$$t_{fluid\_d} = \mathrm{t_d} - 2\left(t_{cable} + t_{pill} + t_{pipe}\right) \quad (11)$$

where

t_u measured total upstream transit time [s];

t_d measured total downstream transit time [s];

t_{cable} transit time through the cable and trigger delay [s];

t_{pill} transit time through the pill [s];

t_{pipe} transit time through the pipe wall [s].

The transit time through the pill and the cable is given by the manufacturer for each pair of transducers.

The transit time through the pipe wall depend on the pipe material, the angle of incidence and the wall thickness and can be calculated with eq. (12).

$$t_{pipe} = \frac{L_{\mathrm{pipe}}}{\mathrm{c}_{\mathrm{pipe}}} \tag{12}$$

$$L_{pipe} = \frac{s}{\cos(\beta)} \tag{13}$$

$$\beta = \arcsin\left(\frac{\sin(\alpha)\cdot c_{pipe}}{c_{pill}}\right) \tag{14}$$

where

L_{pipe}	path length in the pipe wall [m];
c_{pipe}	speed of sound in pipe material [m/s];
β	angle of incidence of the pipe wall [°].

The separation X from pill to pill (cf. Fig. 2 – 5) between the transducers is calculated with eq. (15). This value is needed to ensure a reliable amplitude signal and good signal quality. It affects the measurement uncertainty in an indirect way.

$$X = D_i \cdot \tan(\gamma)\cdot(N+1) + 2\cdot\left(s\cdot\tan(\beta) + Y_{pill}\cdot\tan(\alpha) - X_{pill}\right) \tag{15}$$

where

X	separation between the two transducers [m];
Y_{pill}	vertical distance between sensor surface and wave emitting piezo quarz [m] (cf. Fig. 5);
X_{pill}	horizontal distance between piezo quarz and sensor front surface [m] (cf. Fig. 5).

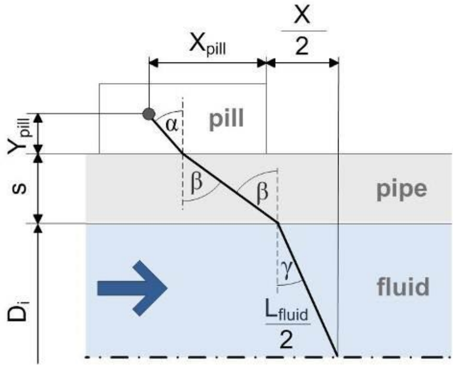

Fig. 5: Scheme for the pill to pill separation calculation

3. THEORETICAL MEASUREMENT UNCERTAINTY

The theoretical measurement uncertainty can be calculated with the Gaussian law of error propagation out of the involved parameters, assuming that all errors can be treated as spurious errors. Some of the individual measurement uncertainties are calculated, others are given based on experience or literature references. The relative measurement uncertainty of the CATT flow rate is calculated by

$$f_{\mathrm{Q}} = \sqrt{f_{\mathrm{K}}^{\;2} + f_{\mathrm{D_i}}^{\;2} + f_{\bar{v}}^{\;2}} \tag{16}$$

where

f_Q	relative measurement uncertainty of flow rate [%];
f_K	relative measurement uncertainty of flow profile correction factor [%];
f_{D_i}	relative measurement uncertainty of internal pipe diameter [%];
$f_{\bar{v}}$	relative measurement uncertainty of line average velocity along the path [%].

The uncertainty of the flow profile correction factor (K) is defined with 0.335 % by Sanderson and Yeung [1].

The relative measurement uncertainty of the internal pipe diameter is defined as

$$f_{\mathrm{D_i}} = \frac{1}{\mathrm{D_a} - 2\mathrm{s}} \cdot \sqrt{e_{\mathrm{D_a}}{}^2 + 4 \cdot e_{\mathrm{s}}{}^2} \tag{17}$$

where

e_{D_a} absolute measurement uncertainty of outer pipe diameter [m];

e_s absolute measurement uncertainty of pipe wall thickness [m].

The absolute measurement uncertainty of the outer pipe diameter depends on the type of measurement used. If the diameter is measured with a calliper the absolute measurement uncertainty (e_{Da}) is estimated with ±0.2 mm. If the diameter is determined by a measurement of the circumference an absolute uncertainty of ±2 mm is appropriate. An absolute measurement uncertainty of ±0.01 mm of the wall thickness is determined in the calibration certification of the wall thickness measurement device.

The line average velocity is the most important value of CATT flow rate measurements. Its measurement uncertainty is

$$f_{\bar{v}} = \sqrt{\left(\frac{\partial \bar{v}}{\partial L_{fluid}} \cdot f_{L_{fluid}}\right)^2 + \left(\frac{\partial \bar{v}}{\partial \gamma} \cdot f_{\gamma}\right)^2 + \left(\frac{\partial \bar{v}}{\partial \Delta t} \cdot f_{\Delta t}\right)^2 + \left(\frac{\partial \bar{v}}{\partial t_{fluid\_u}} \cdot f_{t_{fluid\_u}}\right)^2 + \left(\frac{\partial \bar{v}}{\partial t_{fluid\_d}} \cdot f_{t_{fluid\_d}}\right)^2}$$
$$= \sqrt{f_{L_{fluid}}{}^2 + \left(-\frac{e_{\gamma}}{\tan(\gamma)}\right)^2 + \left(\frac{e_{\Delta t}}{\Delta t}\right)^2 + \left(-\frac{e_{t_{fluid\_u}}}{t_{fluid\_u}}\right)^2 + \left(-\frac{e_{t_{fluid\_d}}}{t_{fluid\_d}}\right)^2} \tag{18}$$

with

$$\frac{\partial \bar{v}}{\partial L_{fluid}} = \frac{(N+1) \cdot \Delta t}{2 \cdot \sin(\gamma) \cdot t_{fluid\_d} \cdot t_{fluid\_u}};$$

$$\frac{\partial \bar{v}}{\partial \gamma} = -\frac{\cos(\gamma) \cdot L_{fluid} \cdot (N+1) \cdot \Delta t}{2 \cdot \sin^2(\gamma) \cdot t_{fluid\_d} \cdot t_{fluid\_u}};$$

$$\frac{\partial \bar{v}}{\partial \Delta t} = \frac{L_{fluid} \cdot (N+1)}{2 \cdot \sin(\gamma) \cdot t_{fluid\_d} \cdot t_{fluid\_u}};$$

$$\frac{\partial \bar{v}}{\partial t_{fluid\_u}} = -\frac{L_{fluid} \cdot (N+1) \cdot \Delta t}{2 \cdot \sin(\gamma) \cdot t_{fluid\_u}{}^2 \cdot t_{fluid\_d}};$$

$$\frac{\partial \bar{v}}{\partial t_{fluid\_d}} = \frac{L_{fluid} \cdot (N+1) \cdot \Delta t}{2 \cdot \sin(\gamma) \cdot t_{fluid\_d}{}^2 \cdot t_{fluid\_u}};$$

where

$\frac{\partial \bar{v}}{\partial L_{fluid}}$ partial derivative of $\bar{v}$ with respect to L_{fluid} [-];

$\frac{\partial \bar{v}}{\partial \gamma}$ partial derivative of $\bar{v}$ with respect to γ [-];

$\frac{\partial \bar{v}}{\partial \Delta t}$ partial derivative of $\bar{v}$ with respect to Δt [-];

$\frac{\partial \bar{v}}{\partial t_{fluid\_u}}$ partial derivative of $\bar{v}$ with respect to t_{fluid_u} [-];

$\frac{\partial \bar{v}}{\partial t_{fluid\_d}}$ partial derivative of $\bar{v}$ with respect to t_{fluid_d} [-];

and

$f_{L_{fluid}}$ relative measurement uncertainty of path length of the acoustic wave in fluid [%];

e_{γ} absolute measurement uncertainty of angle of the acoustic path in fluid [rad];

$e_{\Delta t}$ absolute measurement uncertainty of measured transit time difference [s];

$e_{t_{fluid\_u}}$ absolute measurement uncertainty of transit time of the upstream acoustic wave in fluid [s];

$e_{t_{fluid\_d}}$ absolute measurement uncertainty of transit time of the downstream acoustic wave in fluid [s].

The transit time difference can be determined with an accuracy of $\pm 10^{-9}$ s.

The relative measurement uncertainty of the path length in fluid (L_{fluid}) includes the uncertainty of the internal pipe diameter and the angle of acoustic path in fluid

$$f_{L_{fluid}} = \sqrt{\left(\frac{\partial L_{fluid}}{\partial D_i} \cdot \frac{e_{D_i}}{L_{fluid}}\right)^2 + \left(\frac{\partial L_{fluid}}{\partial \gamma} \cdot \frac{e_{\gamma}}{L_{fluid}}\right)^2} = \sqrt{\left(\frac{e_{D_i}}{D_i}\right)^2 + \left(\tan(\gamma) \cdot e_{\gamma}\right)^2} \quad (19)$$

with

$$\frac{\partial L_{fluid}}{\partial D_i} = \frac{1}{\cos(\gamma)} \ ;$$

$$\frac{\partial L_{fluid}}{\partial \gamma} = \frac{\sin(\gamma) \cdot D_i}{\cos^2(\gamma)} .$$

The angle of the acoustic path in fluid is calculated with a transposed version of Snell’s law of refraction

$$e_{\gamma} = \sqrt{\left(\frac{\partial \gamma}{\partial \alpha} \cdot e_{\alpha}\right)^2 + \left(\frac{\partial \gamma}{\partial c_{fluid}} \cdot f_{c_{fluid}} \cdot c_{fluid}\right)^2 + \left(\frac{\partial \gamma}{\partial c_{pill}} \cdot e_{c_{pill}}\right)^2} \quad (20)$$

with

$$\frac{\partial \gamma}{\partial \alpha} = \frac{\cos(\alpha) \cdot c_{fluid}}{\sqrt{c_{pill}^2 - \sin^2(\alpha) \cdot c_{fluid}^2}} \ ;$$

$$\frac{\partial \gamma}{\partial c_{fluid}} = \frac{\sin(\alpha)}{\sqrt{c_{pill}^2 - \sin^2(\alpha) \cdot c_{fluid}^2}} \ ;$$

$$\frac{\partial \gamma}{\partial c_{pill}} = -\frac{\sin(\alpha) \cdot c_{fluid}}{c_{pill} \cdot \sqrt{c_{pill}^2 - \sin^2(\alpha) \cdot c_{fluid}^2}} \ ;$$

where

$\frac{\partial \gamma}{\partial \alpha}$ partial derivative of γ with respect to α [-];

$\frac{\partial \gamma}{\partial c_{fluid}}$ partial derivative of γ with respect to c_{fluid} [-];

$\frac{\partial \gamma}{\partial c_{pill}}$ partial derivative of γ with respect to c_{pill} [-];

and

e_α	absolute measurement uncertainty of angle of incidence of the transducer [rad];
$f_{c_{fluid}}$	absolute measurement uncertainty of speed of sound in fluid [%];
$e_{c_{pill}}$	absolute measurement uncertainty of speed of sound in pill material [m/s].

An absolute measurement uncertainty of $\pm 10^{-2}$ rad for the angle of incidence a and ±20 m/s for the speed of sound in pill is estimated.

The speed of sound in water is approximated with a formula including pressure and temperature of the fluid.

$$f_{c_{fluid}} = f_{c_{water}} = \sqrt{\left(\frac{0.156 \cdot e_p}{p}\right)^2 + \left(\frac{5.011 - 0.11018 \cdot \vartheta + 6.65E-4 \cdot \vartheta^2}{\vartheta} \cdot e_\vartheta\right)^2} \qquad (21)$$

where

e_p	absolute measurement uncertainty of pressure [bar];
e_ϑ	absolute measurement uncertainty of fluid temperature [°C].

Pressure inside of the pipe can be measured with an accuracy of $\pm 10^{-2}$ bar and the temperature with an accuracy of ±1 C°.

The transit times in the pill and the cable can be determined very accurately, thus these errors are negligible. The measurement uncertainty of the up- and downstream transit time is determined with

$$e_{t_{fluid\_u}} = \sqrt{e_{t_u}^{\ 2} + 4 \cdot e_{t_{pipe}}^{\ 2}} \qquad (22)$$

$$e_{t_{fluid\_d}} = \sqrt{e_{t_d}^{\ 2} + 4 \cdot e_{t_{pipe}}^{\ 2}} \qquad (23)$$

where

e_{t_u}	absolute measurement uncertainty of the measured total upstream transit time [s];
e_{t_d}	absolute measurement uncertainty of the measured total downstream transit time [s];
$e_{t_{pipe}}$	absolute measurement uncertainty of transit time through the pipe wall [s].

Measurement uncertainty of up- and downstream transit time can be determined with $\pm 10^{-7}$ s.

The measurement uncertainty of transit time through the pipe wall is

$$e_{t_{pipe}} = \sqrt{\left(\frac{e_{L_{pipe}}}{c_{pipe}}\right)^2 + \left(\frac{L_{pipe} \cdot e_{c_{pipe}}}{c_{pipe}^{\ 2}}\right)^2} \qquad (24)$$

where

$e_{L_{pipe}}$	absolute measurement uncertainty of path length in the pipe wall [m];
$e_{c_{pipe}}$	absolute measurement uncertainty of speed of sound in pipe wall material [m/s].

An assumption of ±100 m/s absolute measurement uncertainty for the speed of sound in pipe wall material is appropriate. This equates approximately to 3 percent of the absolute value.

The errors of the pipe wall thickness and the angle β influence the measurement uncertainty of the length of path in the pipe wall

$$e_{L_{pipe}} = \sqrt{\left(\frac{\partial L_{pipe}}{\partial s} \cdot e_s\right)^2 + \left(\frac{\partial L_{pipe}}{\partial \beta} \cdot e_\beta\right)^2} \qquad (25)$$

with

$$\frac{\partial L_{pipe}}{\partial s} = \frac{1}{\cos(\beta)} \ ;$$

$$\frac{\partial L_{pipe}}{\partial \beta} = \frac{\sin(\beta) \cdot s}{\cos^2(\beta)} \ ;$$

where

e_β absolute measurement uncertainty of angle of incidence in the pipe wall [rad].

The calculation of the relative measurement uncertainty of β is defined as

$$e_\beta = \sqrt{\left(\frac{\partial \beta}{\partial \alpha} \cdot e_\alpha\right)^2 + \left(\frac{\partial \beta}{\partial c_{pipe}} \cdot e_{c_{pipe}}\right)^2 + \left(\frac{\partial \beta}{\partial c_{pill}} \cdot e_{c_{pill}}\right)^2} \tag{26}$$

with

$$\frac{\partial \beta}{\partial \alpha} = \frac{\cos(\alpha) \cdot c_{pipe}}{\sqrt{c_{pill}^{\ 2} - \sin^2(\alpha) \cdot c_{pipe}^{\ 2}}} \ ;$$

$$\frac{\partial \beta}{\partial c_{pipe}} = \frac{\sin(\alpha)}{\sqrt{c_{pill}^{\ 2} - \sin^2(\alpha) \cdot c_{pipe}^{\ 2}}} \ ;$$

$$\frac{\partial \beta}{\partial c_{pill}} = -\frac{\sin(\alpha) \cdot c_{pipe}}{c_{pill} \cdot \sqrt{c_{pill}^{\ 2} - \sin^2(\alpha) \cdot c_{pipe}^{\ 2}}} \ ;$$

where

$\frac{\partial \beta}{\partial \alpha}$ partial derivative of β with respect to α [-];

$\frac{\partial \beta}{\partial c_{pipe}}$ partial derivative of β with respect to c_{pipe} [-];

$\frac{\partial \beta}{\partial c_{pill}}$ partial derivative of β with respect to c_{pill} [-].

4. MEASURED CASES IN THE LABORATORY AND THE FIELD

The laboratory tests with the CATT measurement device were carried out at the Hydro Laboratory of the Hochschule Luzern. Laboratory measurements were carried out at 8 different pipes with various transducer configurations (Tab. 1).

For all installations the condition of 50 straight diameters upstream and 10 straight diameters downstream from any flow disturbance were fulfilled, in accordance with Sira [5] and the manufacturers specifications. Additional tests were carried out to investigate the influence of upstream flow disturbances. The reference flow rates were measured with a calibrated magnetic inductive flow meter (MID) or by mass and time measurements.

The internal pipe diameters varied from 13.15 – 502.9 mm and the wall thickness varied from 2.01 – 11.0 mm at the different pipes. The measured flow rates ranged from 0.03 to 1044 l/s and the associated average velocities from 0.25 to 5.10 m/s. All velocities lay within the specified and calibrated measurement range of the device. At least two different flow rates were measured for each pipe. The data acquisition rate was always 1 Hz.

In addition to the measurements in laboratory field tests were carried out. The CATT instrument was tested in three HHP (Tab. 1).

method: CATT measurement			direct through	reflection					cross path	various flow rates	reproducibility	repeatability	pipe ovality	variation of the entered parameter						disturbances
			0	1	2	3	4	5						ϑ	c_{pipe}	X	s	D_a	k	
Laboratory	D_i = 13.15 mm	FSS	X		X	X	X	X		X							X	X		
	D_i = 27.40 mm	FSS / FSQ	X	X	X	X	X	X		X				X			X	X	X	
	D_i = 50.00 mm	FSS / FSQ	X	X	X	X	X	X		X	X	X		X	X	X			X	X
	D_i = 100.0 mm	FSQ		X						X										
	D_i = 149.0 mm	FSQ / FSM	X	X	X	X				X		X	X							X
	D_i = 159.5 mm	FSM		X						X										
	D_i = 496.4 mm	FSM	X						X	X	X	X	X							X
	D_i = 502.9 mm	FSM	X	X					X	X										
Field	HPP Sassello	FSM		X						X										
	HPP Filisur	FSM	X							X										
	HPP Fieschertal	FSM	X							X										

Tab. 1: Measured cases with the CATT measurement device

4.1. Laboratory measurements

As shown in Fig. 1 some pipe diameters (25 – 70 mm and 100 – 200 mm) can be measured with two transducer pairs. To evaluate which transducer pair is best suited within these two ranges, both sensors were tested at pipes with internal diameters of 27.4, 50 and 149 mm (Fig. 6).

With the formulas in section 2 the influencing of quantities on the estimation of the total measurement uncertainty are given. The major influence comes from the pipe wall thickness and the outer diameter [5]. These dimensions are required to calculate the transit time through the pipe wall, eq. (12), and the internal diameter, eq. (4), from which the cross-sectional area, eq. (3), and the path length in the fluid, eq. (5), is calculated in turn. Relevant influences caused by the temperature (7), the speed of sound in the pipe (11) and the internal pipe wall roughness, which determines the flow profile correction factor (2), were also investigated. The influence of a incorrectly entered number for the separation, when programming the device, has been tested. This leads to a poor signal quality or amplitude. For all these tests, the clamp-on arrangement was installed properly and only selected parameters were varied in the user interface.

Six test series were evaluated under equal conditions, equal installation arrangement and during a total time of 30 minutes to determine the repeatability. 240 data points were measured during four minutes in each test series. Two different flow rates through two different pipes were measured.

The reproducibility was determined on the basis of six measurement series of 4 minutes, with the FSM and the FSS transducers. The transducer pairs were removed after each test series and clamped-on again at the same position. The amount of couplant lube was checked during the reproducibility tests.

The influences of disturbances caused by vibrations were tested in two cases by irregular hits of a plastic hammer on the pipe, near the transducers. The influence of an upstream 70° bend was investigated by installing the CATT device at two distances downstream from the disturbance.

4.2. Field measurements

At HPP in Sassello the flow rate through each of the two nozzles of the 11 MW horizontal Pelton turbine was measured. The CATT flow meters were installed immediately downstream from the bend on the upper and the lower injectors (Fig. 7). They were clamped-on horizontally with one acoustic wall reflection (N = 1). The pipes were coated with epoxy of about 1 mm thickness and the surfaces of the cast pipes were uneven. The clamp-on arrangement was installed before and after the turbine revision, at the same position and with the same parameters set in the program. Simultaneous thermodynamic efficiency measurements took place, and accordingly the CATT measurements could be compared to the absolute flow rate, which resulted from the thermodynamic efficiency measurement.

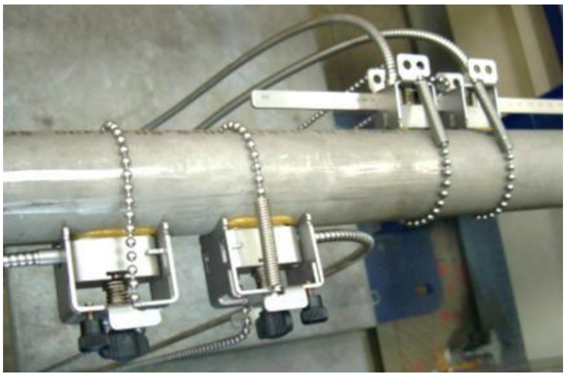

Fig. 6: CATT measurement at D_i=50 mm pipe

Fig. 7: CATT measurement at HPP Sassello

5. LABORATORY TEST RESULTS

5.1. Best transducer arrangement for various conditions

The measurement series at three diameters and six different flow rates with the FSS transducer pair achieved best accuracy with 1, 3, 4 and 5 acoustic wall reflections. It is not advisable to apply the direct through arrangement (N = 0) for measurement of the flow rate through small pipes (internal diameter smaller than 70 mm) because the path length and the associated transit times are too short for accurate measurements.

The reflection type arrangement leads to best results for the majority of the flow rate measurements with the FSQ sensor. The arrangements with 1, 2 or 3 reflections give better results than all other arrangements. No signal could be received with 3 reflections during the measurements at the 149 mm outer diameter pipe.

Reflection (N = 1) or cross-path installations delivered better results than the direct through arrangement for flow rate measurements with the FSM transducers (Fig. 8).

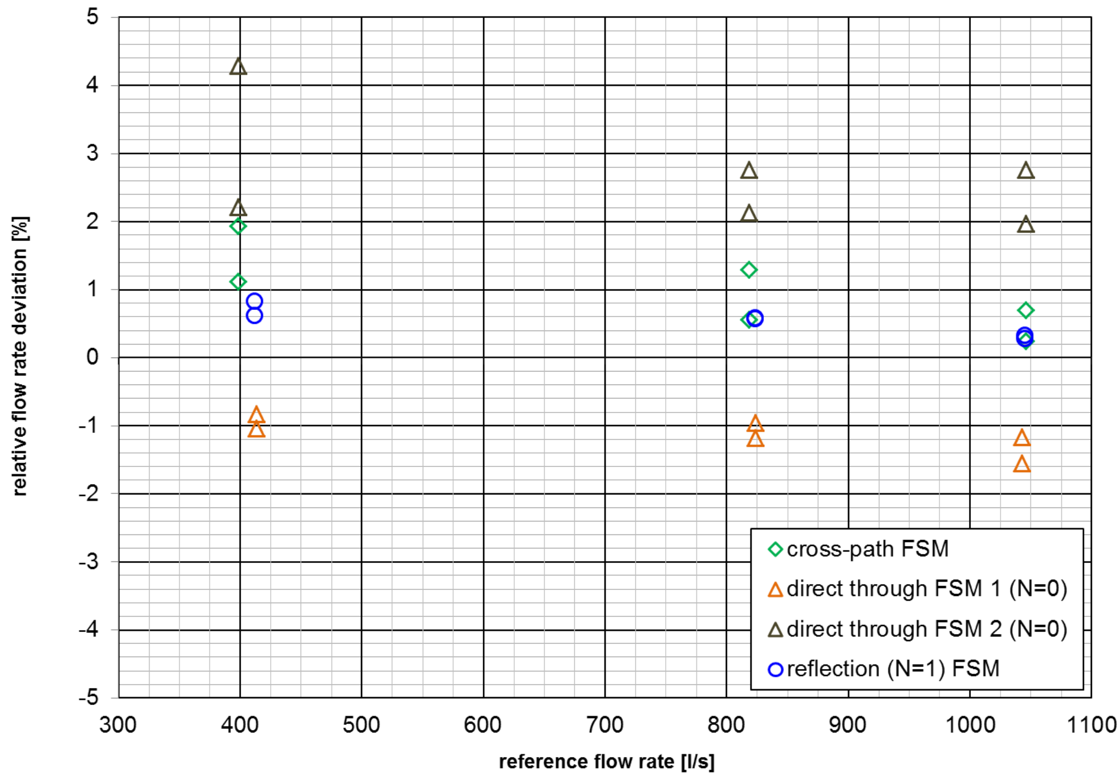

Fig. 8: CATT measurements at D_i=502.9 mm pipe with various installation arrangements

5.2. Repeatability

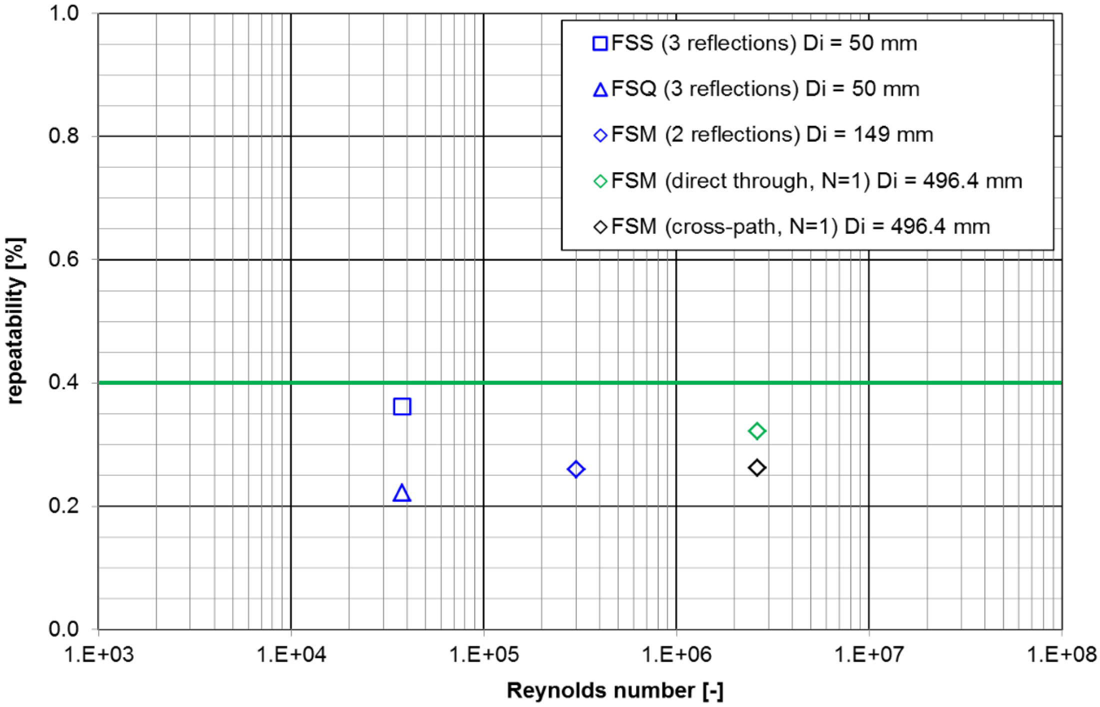

Fig. 9: Repeatability of CATT measurements under varying Reynolds number

The repeatability was determined from 6 measurements, with 240 data points each. The measurement details are described in section 4.1. Flow rates from 1.5 to 40 l/s were measured for the repeatability investigation. The reapeatability for the entire measurement range was measured to be better than 0.4 percent (Fig. 9). The repeatability of 0.4 percent (green line), determined in the measurements, agrees well with the range of 0.15 - 0.5 percent given by Sanderson and Yeung, Sira and BSI [1, 5, 8].

5.3. Reproducibility

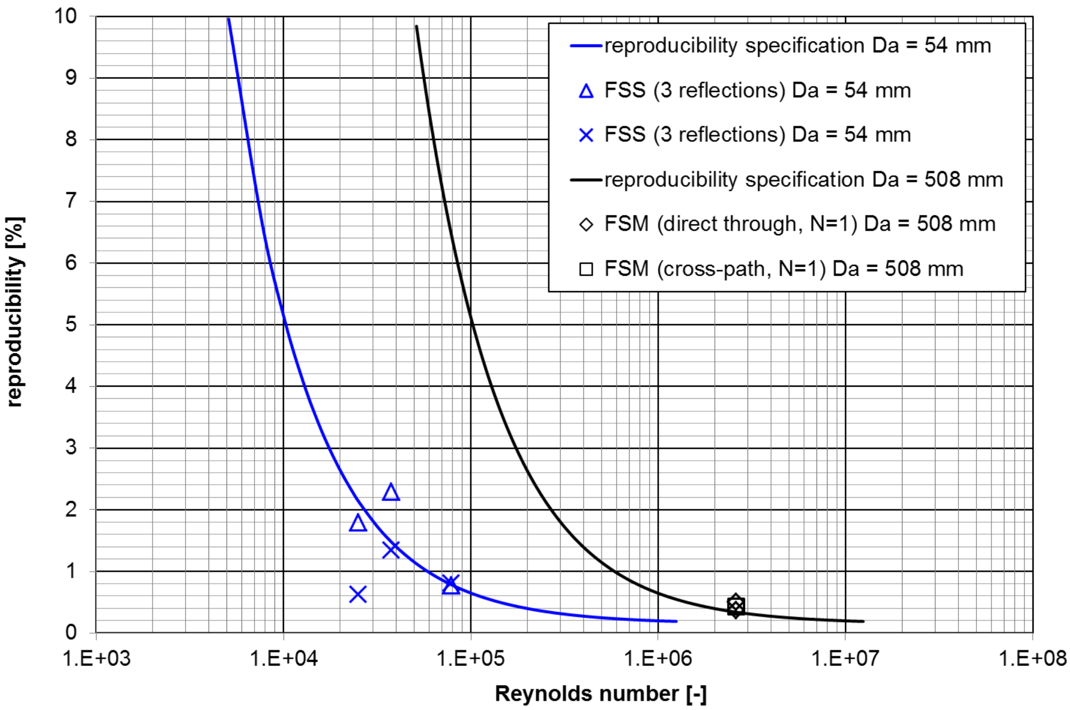

Fig. 10: Reproducibility of CATT measurements under varying Reynolds number

The reproducibility was tested at the 50 and 496.4 mm pipe with the FSM and the FSS transducer pairs for various Reynolds numbers (Fig. 10). More details are given in section 4.1. The sensors were installed in reflection arrangement at both pipes. In order to determine the reproducibility sensors were completely removed and clamped-on again between each measurement and each case was measured 6 times under the identical conditions. The specified reproducibility has a fixed part (±0.15 percent of value) and a varying part (±0.01 m/s) which is a function of the Reynolds number range. The specifications could be confirmed by the present measurements.

5.4. Total CATT measurement uncertainty and the influence of the variables

The test cases were measured to evalute the total measurement uncertainty due to varying separately boundary conditions, with appropriate installation and correct entered other boundary conditions. The relative flow rate deviation is calculated with (26)

$$\Delta Q = \frac{Q - Q_{ref}}{Q_{ref}} \cdot 100\% \tag{26}$$

where

ΔQ	relative flow rate deviation [%];
Q	CATT flow rate [l/s];
Q_{ref}	reference flow rate [l/s] (MID or mass at time);

with $\frac{s}{D_i} \leq 0.04$

The measurement uncertainty is specified for our device by the manufacturer with 1 percent of value, ±0.01 m/s. The blue shaded area is referred to the fixed percentage and the green area represents the ±0.01 m/s, which varies over the Reynolds number range (Fig. 11). The sum of these two parts is the specified measurement uncertainty for the pipe with 27.4 mm internal pipe diameter.

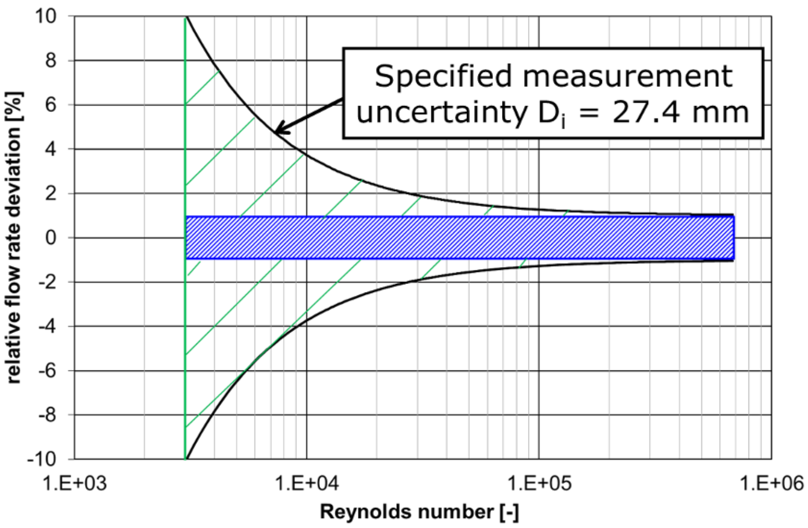

Fig. 11: Fixed and varying part of measurement uncertainty

With Sanderson and Yeung, Jung and Seong, Eisenhauer, BSI and Cape et al. [1, 2, 7, 8, 9] measurement uncertainties between 1 and 5 percent of value are given, but mostly around 2 percent.

The relative flow rate deviations of the CATT measurements with the FSS, FSQ and FSM sensors are separately displayed in three diagrams (Fig. 12 – 14). The results are plotted as a function of the Reynolds number. The blue, black and green lines are the specified measurement uncertainties of the manufacturer, calculated for the measured pipe diameters and the specified velocity range from 0.1 to 25 m/s. Supposed outliers in the measurement were eliminated from these figures. Many points in these diagrams 12 – 14 are located outside of the specified range, because appropriate measurement conditions were not met.

The measurement uncertainty of the FSS transducer was determined in the specified diameter range between 10 and 70 mm internal pipe diameter. The measurement uncertainty was measured for three different pipes within the specified diameter range (Fig. 12). The specified ranges are plotted as solid lines in the diagrams. The measurement results lie mostly outside of the specifications for all three pipes. Small pipes from 10 to 25 mm internal pipe diameter can be measured only by FSS sensor, but generally tests with the FSQ sensor gave smaller uncertainties in the overlapping diameter range from 25 – 70 mm (cf. Fig. 1).

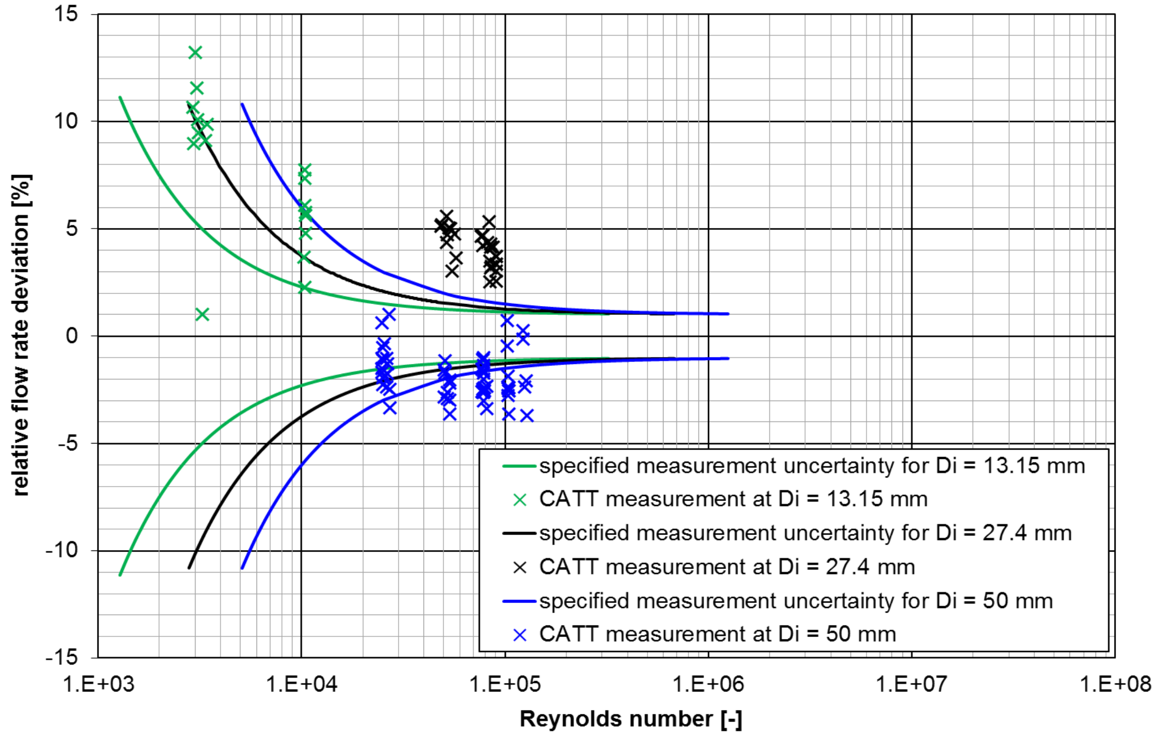

Fig. 12: Relative deviations with the FSS transducer

The FSQ transducers can be used at pipes with internal pipe diameters from 25 to 200 mm according to the specifications. They were tested at 3 pipes with outer pipe diameters of 27.4, 50 and 149 mm (Fig. 13). Most of the test results lay inside or close to the specifications.

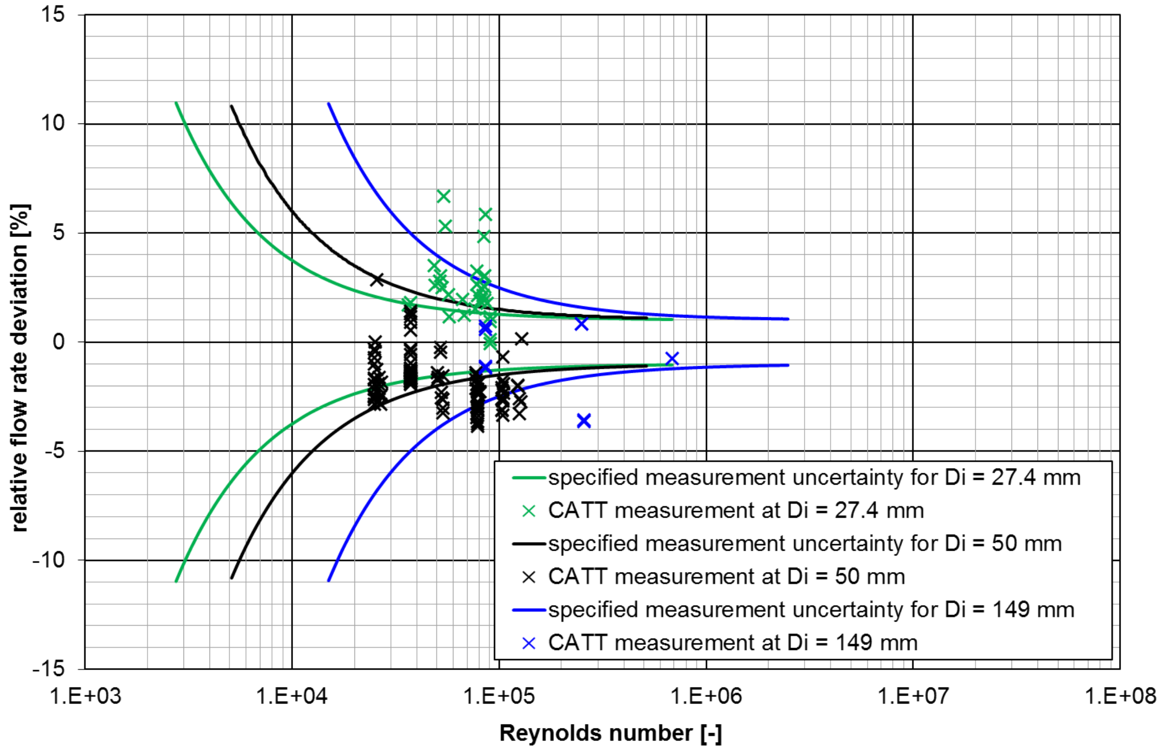

Fig. 13: Relative deviations with the FSQ transducer

The FSM transducer pair is specified for pipes from 100 to 2000 mm (Fig. 14). Measurements were performed at pipes with 149 mm and 502.9 mm. The specified measurement uncertainty could only be reached at the larger pipe, which leads to a reduction of the appropriate range to 200 - 2000 mm for the FSM sensor.

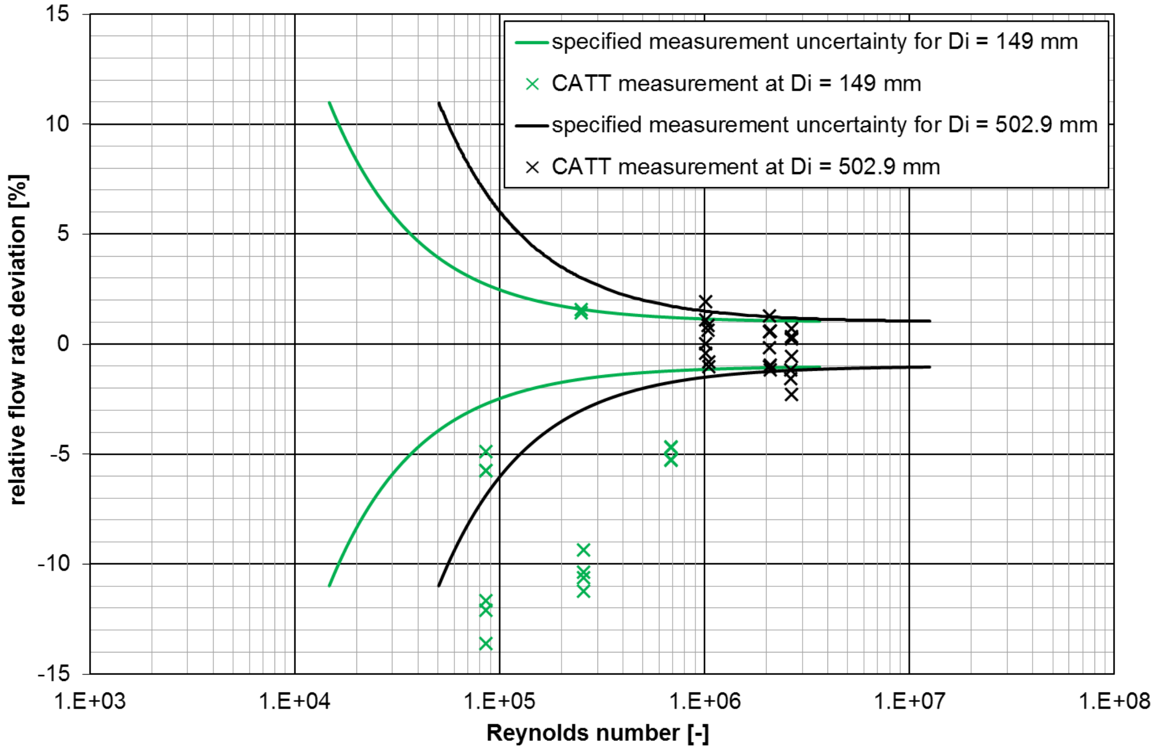

Fig. 14: Relative deviations with the FSM transducer

The three transducer pairs have overlapping application ranges (Fig. 1). According to the present measurements results the appropriate internal diameter ranges for each sensor should be reduced (Fig. 15): For the FSS transducers to 10 - 25 mm, for the FSQ to 25 - 200 mm, and for the FSM to 200 to 2000 mm.

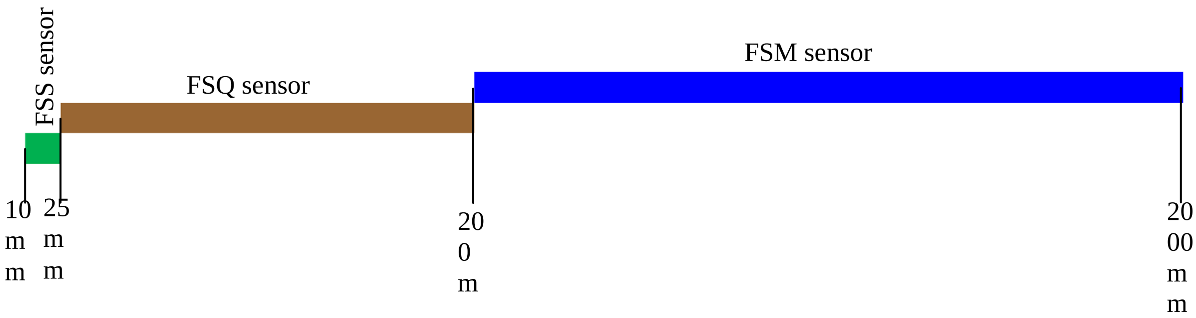

Fig. 15: Appropriate internal pipe diameter range for the FSS, FSQ and FSM transducer

5.4.1. Diameter variation

The variation of the entered outer diameter at the user interface has a linear influence on the flow rate deviation. This linear dependence was measured with the FSS and the FSQ transducers at the pipe with 27.4 mm diameter and are confirmed by Cape et al. [9] (Fig. 16).

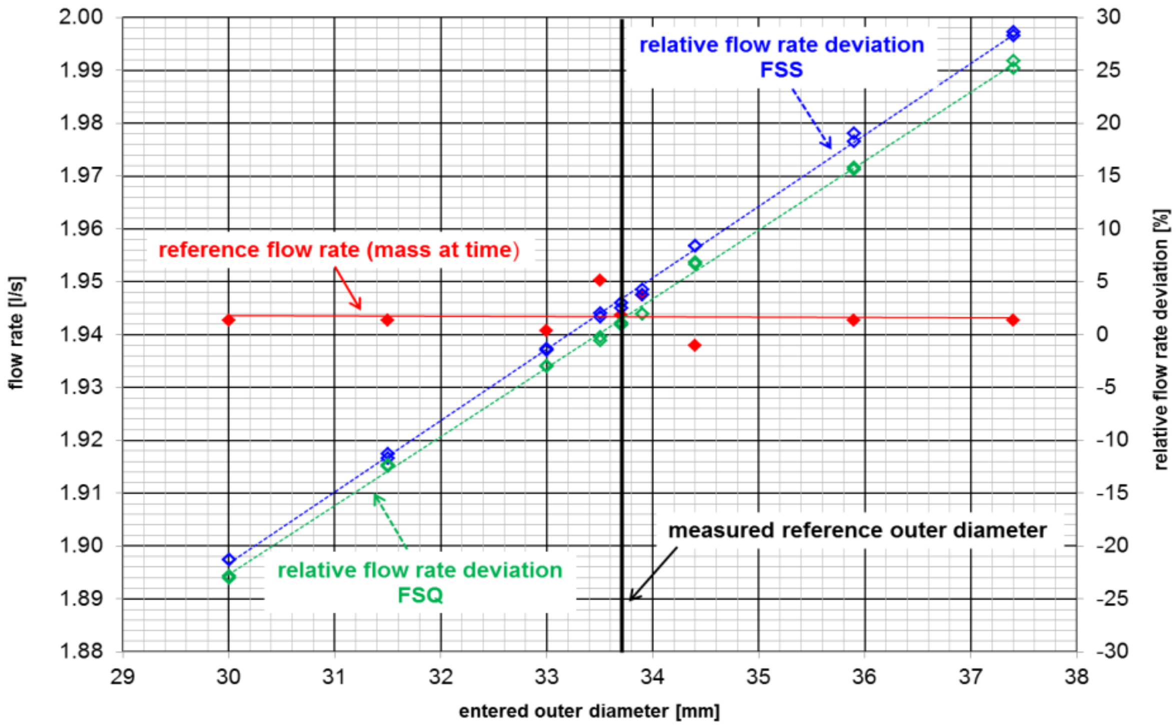

Fig. 16: Relative deviations in function of varying diameter

5.4.2. Wall thickness variation

The variation of the entered wall thickness at the user interface also showed linear influence on the flow rate deviation (Fig. 17). These measurements were performed at the smallest measured pipe with internal diameter 13.15 mm and with the FSS transducer.

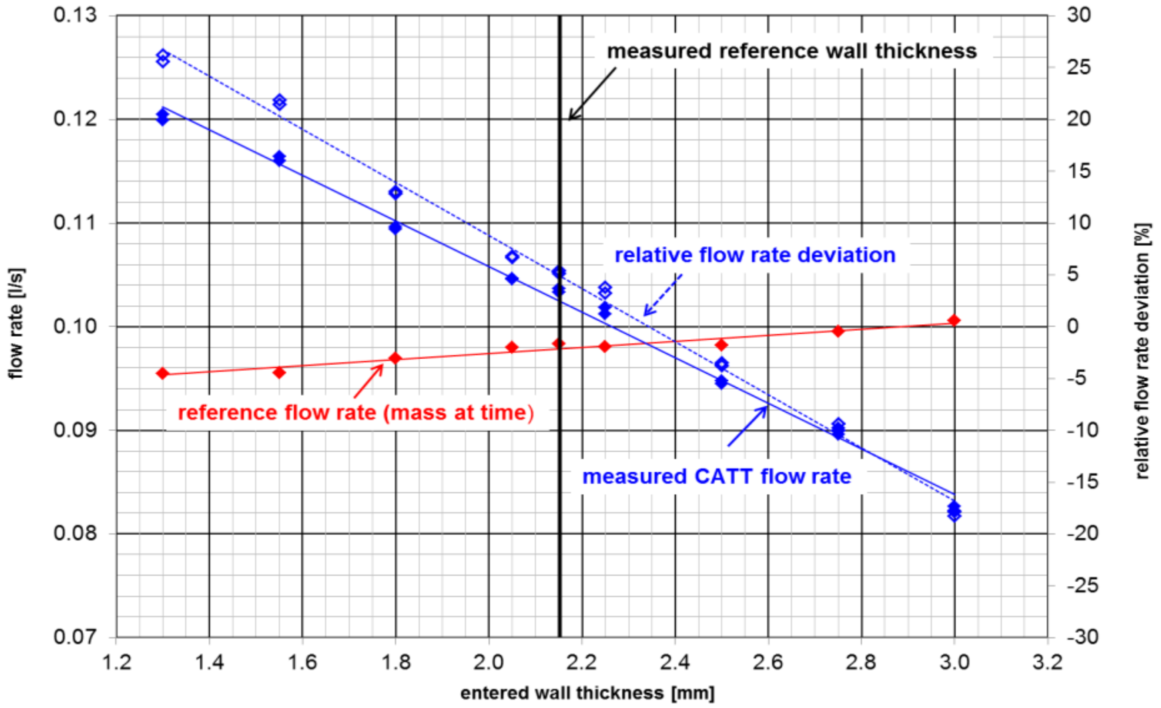

Fig. 17: Relative deviations in function of varying wall thickness

5.4.3. Temperature variation

Sira [5] as well as BSI [8] state that a temperature variation of 15 °C affects the flow rate by less than 0.4 percent. Out of the present laboratory tests a deviation of less than 0.5 percent was measured with a temperature error of 15 °C. With accurate temperature measurements (errors smaller than 2 °C) the influence of temperature becomes negligible.

5.4.4. Variation of speed of sound in the pipe

An increase of speed of sound in the pipe material by 12.5 percent, gives rise to a positive error of the flow rate of 0.25 percent. This linear trend can be confirmed in negative direction of the input error. For defined or known pipe material the flow rate error becomes negligible.

5.4.5. Internal pipe wall roughness variation

The entered internal pipe wall roughness has influence on the flow profile correction factor, which is used for the calculation of the flow rate eq. (3), as decribed by Sanderson and Yeung [1] and Jung and Seong [2]. An entered error in this value causes a false approximation of the flow profile and accordingly a false correction of the mean velocity. The entered wall roughness was varied from 0.01 to 2.0 mm. The approximated value for the measured stainless steel pipe without seam is 0.1 mm. The measured errors of the varying values compared to the approximated roughness causes maximum errors from +2 percent at 0.01 mm to –4.7 percent at 2.0 mm. The trend of the deviation is nonlinear.

5.4.6. Separation variation

The measurement device calculated the optimal separation between the sensors out of correct entered input data. This given separation distance was adjusted and under this conditions the separation distance was entered falsely. A separation variation of ±5 percent lead to a insignificant flow rate error of 0.1 percent and is accordingly negligible.

5.5. Influence of disturbances on CATT measurements

At the 496.4 mm pipe the FSM sensors were firstly installed coplanar and afterwards with 90° phase shift to the 70° bend to determine the error caused by upstream disturbances and its orientation relative to the bend. As shown in the diagram below (Fig. 18), an undisturbed upstream length to the bend of approximately 3 or 12 diameters (D) is too short. The results with 12 D are better than with 3 D. The blue datapoints on the diagram are measured with an CATT installation with 90° phase shift to the bend and delivered better results than the coplanar installation data points in green.

Sanderson and Yeung, Sira, Kumar et al. and BSI [1, 5, 6, 8] and the specifications of the used flow meter advice to observe the following lengths (S_{up}) to upstream disturbances for accurate measurements:

- $S_{up} \geq 10$ D reducer, holes, closed flange
- $S_{up} \geq 25$ D expancer, bend, orifice
- $S_{up} \geq 50$ D valve, pump, double bend

Downstream of the CATT flow meter installations an undisturbed straight pipe length should follow. It is appropriate to follow the recommendations given in literature. The following undisturbed downstream pipe lengths (S_{down}) are recommended by Sanderson and Yeung, Sira, Kumar et al. and BSI [1, 5, 6, 8] and the instrument manual:

- $S_{down} \geq 5$ D reducer, holes, closed flange, expancer, bend, orifice
- $S_{down} \geq 10$ D valve, double bend
- $S_{down} \geq 25$ D pump

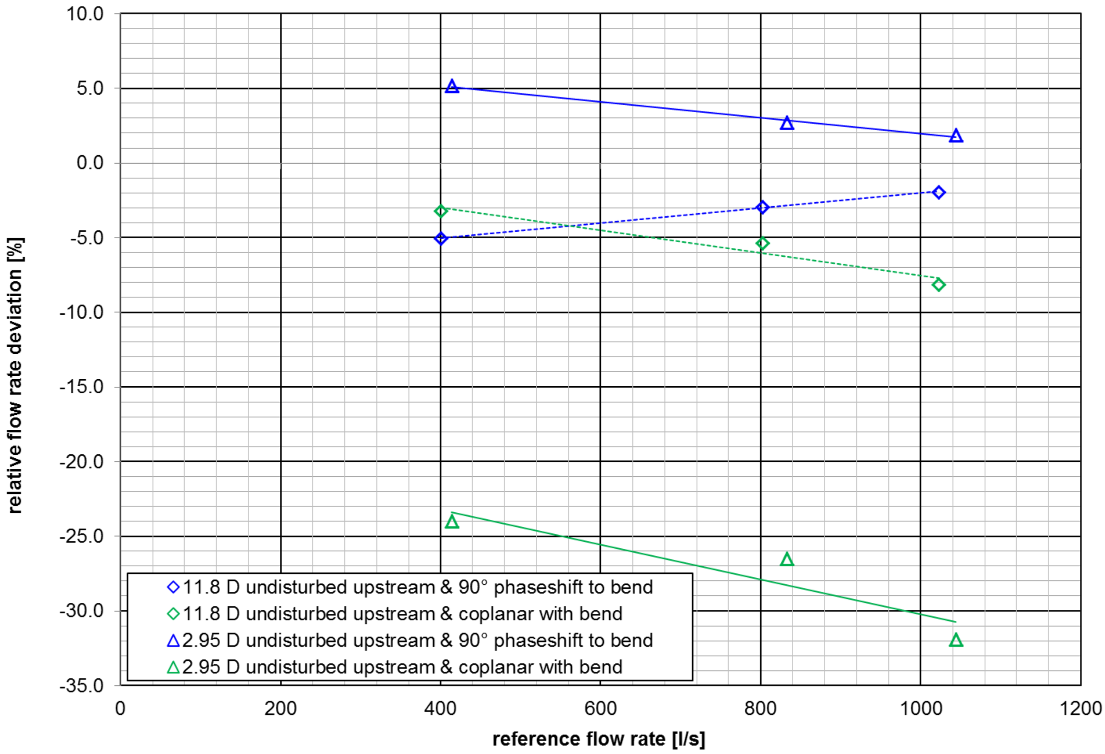

Fig. 18: Influence on relative flow rate deviation by upstream disturbances

Vibrations induced by hits of a plastic hammer on the pipe did not cause measurement errors. This was tested in two situations.

5.6. Influence of varying pressure

A variation of pressure has only small influence on the flow rate deviation and can be neglected for measurements at hydro power plants, BSI [8].

6. RESULTS OF THE FIELD MEASUREMENTS

The hydraulic efficiency of the horizontal two nozzle Pelton turbine in Sassello was measured with the absolute thermodynamic method and with the CATT index method. In this way the measured index efficiency curve can be compared to the absolute efficiency curve, allowing to eliminate outliers. The flow rate for the index efficiency calculation was measured with a reflection installation with FSM transducers at each of the two injectors of the turbine.

The solid lines in the figure below are the polynomial fits of the thermodynamic tests and the dotted lines are the fits of the index tests (Fig. 20). The comparison shows that the thermodynamic and the index efficiency lie very close together. The shapes of the index efficiency curves lines are identical with those of the thermodynamic efficiency tests. The repeatability in this field test was very good and remained below the values determined in the laboratory tests. The quality of the result of the CATT index measurement is very encouraging, but further experience with field tests is needed for a final conclusion.

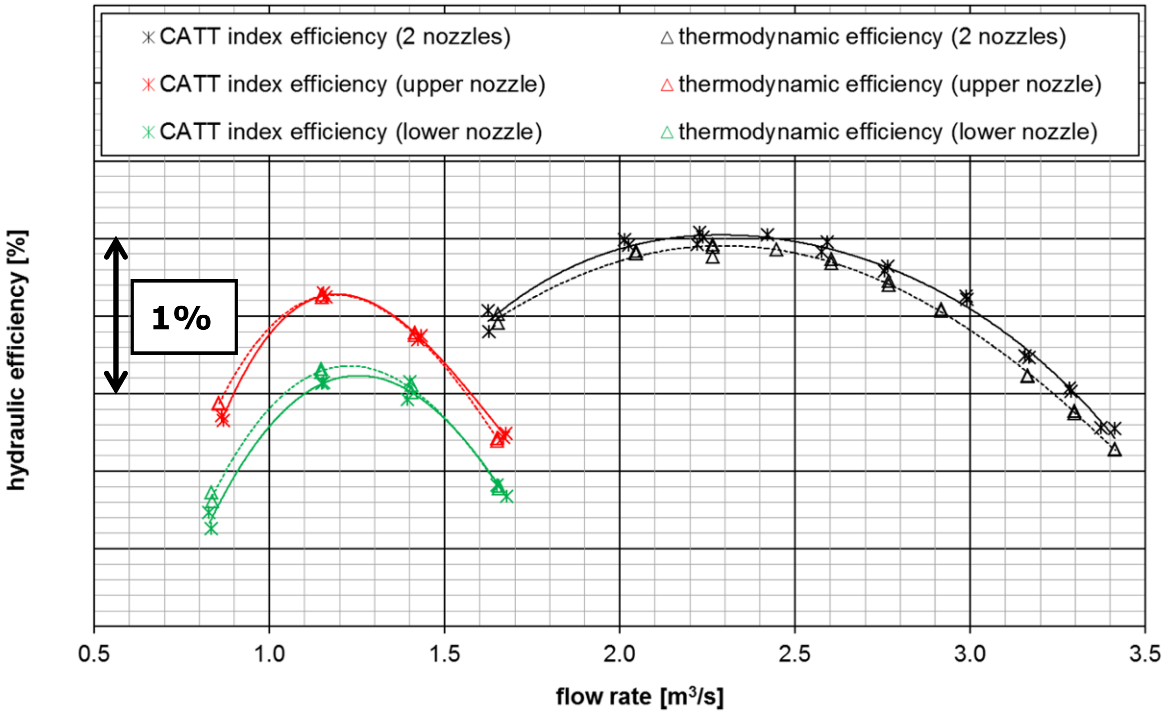

Fig. 20: Comparison between thermodynamic efficiency and CATT index efficiency

7. USABILITY OF CATT FLOW RATE MEASUREMENTS FOR EFFICIENCY TESTS

7.1. Appropriate measurement conditions

A minimum average velocity of 1 m/s has to be present for accurate flow rate measurements with CATT devices, otherwise the relative flow rate deviation exceeds 2 percent. Smooth pipe walls without or with thin coating are needed for high signal amplitudes and quality. The pipe wall roughness has to be below 0.2 mm, because the diffusion of the acoustic signals at the rough wall can affect the signal quality. The CATT flow rate accuracy is affected also by the velocity profile. Well developed flow profiles minimise the error caused by flow profile correction. The needed undisturbed pipe length depends on the obstruction and the arrangement situation (cf. chapter 5.6). Upstream distortions demand longer distances (10 – 50 D) from the measuring section, than downstream disturbances (5 – 25 D).

7.2. Index measurements

The repeatability of the CATT field measurement in Sassello was smaller than that of the laboratory experiment which showed a repeatability of 0.4 percent. Thus the instrument can be adequately used for index measurements. This index measurement method is appropriate for efficiency curve shape control. Additional measurements are still required for verification.

7.3. Comparative efficiency measurements

For comparative efficiency measurements with long time intervals between the measurements a good (small) reproducibility is required. The reproducibility measured in the laboratory could be confirmed only by the field measurements in Sassello. For low Reynolds numbers it was found that the reproducibility is too large for comparative tests. The CATT flow rate measurement is not usable for comparative tests when the transducers are dismanteled inbetween the tests. Also here, more experience and additional field measurements with better reproducibility are needed.

7.4. Absolute efficiency measurements

Absolute flow rate measurements used for efficiency measurements are not possible with CATT instruments, since the measurement uncertainty is too large.

7.5. Additional measurements

CATT flow metering is well suited for leakage flow measurements at the pressure balancing pipe or other pipes with a measurement uncertainty less than 5 percent.

For flow rate measurements in cooling systems a measurement uncertainty of less than 3 percent is possible with CATT devices.

8. CONCLUSION

The carried out laboratory and field measurements mostly confirmed the manufacturer specifications and information published in literature. The present investigations allowed to better understand the suitability and the limitations of the used CATT flow meter with respect to the measuring uncertainty, the installation arrangements, influence of the parameter settings on the result, and possible field applications.

For sufficiently accurate flow rate measurements with CATT devices a minimal average velocity of 1 m/s is needed, otherwise the relative flow rate deviation exceeds 5 percent. Smooth pipe walls without or with thin coating and pipe wall roughness below 0.2 mm are necessary for high signal amplitudes and quality. The required undisturbed pipe length depends on the type of obstruction and the arrangement situation. Upstream distortions require longer distances (10 – 50 D) from the flow meter installation, than downstream disturbances (5 – 25 D). An appropriate installation and arrangement of the sensors on the pipe is essential for accurate measurements. The table for best installation arrangements for various pipe diameters under disturbed or undisturbed flow conditions was established on the basis of performed measurements (Tab. 2).

		undisturbed flow conditions: 50D upstream & 10D downstream without disturbance							disturbed flow conditions: 10D upstream & 2D downstream without disturbance						
method: CATT measurement		direct through	reflection					cross path	direct through	reflection					cross path
		0	1	2	3	4	5		0	1	2	3	4	5	
D_i = 10 mm	FSS	red	yellow	yellow	green	green	green	red	red	red	yellow	green	green	green	red
D_i = 20 mm	FSS	red	yellow	green	green	green	green	red	red	red	yellow	green	green	green	red
D_i = 50 mm	FSQ	red	yellow	green	green	green	yellow	yellow	red	yellow	yellow	green	green	yellow	yellow
D_i = 100 mm	FSQ	yellow	yellow	green	green	green	red	yellow	red	yellow	green	green	yellow	red	yellow
D_i = 150 mm	FSQ	yellow	yellow	green	green	red	red	yellow	red	yellow	green	green	red	red	yellow
D_i = 250 mm	FSM	yellow	green	green	green	red	red	green	red	yellow	yellow	yellow	red	red	green
D_i = 400 mm	FSM	yellow	green	green	red	red	red	green	red	yellow	yellow	red	red	red	green
D_i = 600 mm	FSM	green	green	green	red	red	red	green	yellow	yellow	yellow	red	red	red	green
D_i = 1000 mm	FSM	green	green	green	red	red	red	green	yellow	yellow	yellow	red	red	red	green
D_i = 1500 mm	FSM	green	green	red	red	red	red	green	yellow	yellow	red	red	red	red	green
D_i = 2000 mm	FSM	green	green	red	red	red	red	green	yellow	yellow	red	red	red	red	green

green: appropriate measurement; yellow: possible measurement; red: inaccurate measurement

Tab. 2: Best installations arrangement for various conditions

Index efficiency measurements with CATT flow rates are possible with a repeatability of 0.4 percent. Such index tests are recommended to check the shape of efficiency curves and for elimination of outliers. A reproducibility of smaller than 0.5 percent of the flow rate is needed for comparative efficiency measurements. This value could not be achieved in field measurements, thus comparative efficiency measurements are not feasible without better reproducibility in field tests.

The flow rate measurement uncertainty (f_Q) depends on the pipe diameter, which defines the recommended sensor and the mean velocity of the fluid (Tab. 3). In general, high velocities in large pipes can be measured more accurately than low velocities in small pipes.

	$1\ m/s \leq \bar{v} \leq 5\ m/s$	$5\ m/s \leq \bar{v} \leq 25\ m/s$
FSS (10 mm ≤ Di ≤ 25 mm)	$f_v \leq 5$ %	$f_v \leq 5$ %
FSQ (25 mm ≤ Di ≤ 200 mm)	$f_v \leq 3$ %	$f_v \leq 2$ %
FSM (200 mm ≤ Di ≤ 2000 mm)	$f_v \leq 2.5$ %	$f_v \leq 2$ %

Tab. 3: Reachable measurement uncertainty for CATT flow rate measurements

Absolute efficiency measurements are not possible with CATT flow rates because of the high measurement uncertainty. CATT flow rate measurements are appropriate for cooling systems and for leakage flow determination.

CAD flow metering is not useable for measurements in hydro power plants, because the measurement uncertainty of approximately 10 percent, observed in our measurements, is too large.

The laboratory measurements and the acquired knowledge represent a good base for further investigations in field applications. Additional field tests are needed for more detailed assessments on the usability of CATT flow rate measurements for index efficiency tests.

REFERENCES

[1] Sanderson M. L., Yeung H., "Guidelines for the use of ultrasonic non-invasive metering techniques", Flow Measurement and Instrumentation 13, p. 125-142, 2002.

[2] Jung J. C., Seong P. H., „Estimation of the Flow Profile Correction Factor of a Transit time Ultrasonic Flow Meter for the Feedwater Flow Measurement in a Nuclear Power Plant", IEEE Transactions on nuclear science, Vol. 52, No. 3, 2005.

[3] TUV NEL Ltd., "Good Practice Guide: An Introduction to non-invasive ultrasonic flow metering", Glasgow.

[4] Tresch T., Gruber P., Lottenbach R. "Diagnosis of the acoustic discharge measurement on the basis of temperature monitoring", HSLU, 2004.

[5] Sira Instrument Test and Calibration, "Final report on Clamp-on Transit Time Ultrasonic Flowmeter Performance Evaluation", GBBK/C/03/18, Kent, 2005.

[6] Kumar K., Farande K. U., Thakur N. S., "Comparative studies for installation effects on flow measurement accuracy", Maharashtra, India, 2011.

[7] Eisenhauer D. E., "Using Ultrasonic Flow Meters in Irrigation Applications", NebGuide G1426, Nebraska, 2008.

[8] BSI Standards Publications, "Use of clamp-on (externally mounted) ultrasonic flow-metering techniques for fluid applications - Guide", BSI, BS 8452:2010, 2010.

[9] Cape J., Cook B., Currey A., Hassanli A., Pezzaniti D., Turral H., "Measured in-situ Verification of Meters for Non-Urban Water Supply", Melbourne, 2008.

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