THE PRESSURE-TIME MEASUREMENTS PROJECT AT LTU AND NTNU

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ABSTRACT

The Norwegian University of Science and Technology (NTNU) and Luleå University of Technology (LTU) have during the last two years collaborated in the development of the pressure-time method for hydropower application, also known as Gibson method. The research is motivated by the need of a fast, reliable and cost effective method for low head hydraulic efficiency measurements, i.e., outside the IEC 41 standard. The collaboration has involved the construction of a test rig at NTNU specifically designed to study the pressure-time method. The laboratory test rig allows high accuracy flow measurements and evaluation of different solutions before field tests. Furthermore, the high accuracy and repeatability of such measurements are used for the validation of numerical codes on the matter.

Field tests at Anundsjoe power plant in Sweden have been performed. Simultaneous measurements within and outside the IEC 41 standard were made for comparison.

The laboratory results show that the calculated mean flow rate does not differ much if the distance between the measuring cross-sections is shorter than specified in the standard. However, the uncertainty and spread become larger as the distance between the measurement cross-sections decreases. A slightly velocity dependence is found where the flow gets gradually over estimated with decreasing velocity. In the field test, the difference between the measured discharges (according to and outside the standard) is less than 1% and random.

For the case with bends within the control volume, both the laboratory and field tests show that this will cause an underestimation of the flow. A future aim would be to develop a systematic compensation for this underestimation based on pipe diameter, bend angle and bend radius.

INTRODUCTION

Hydro power is a rather old and clean energy source. Nowadays many plants are in need of refurbishment. Also new power plants are under construction. After construction or refurbishment of hydro power plants efficiency measurements are desirable, usually for guarantee reasons. There are well known methods for this purpose, e.g., thermo dynamic, current meter, pressure-time and ultra sonic. Most of these methods have high accuracy when used at favorable conditions. However, in the case of low head power plants there are problems with most methods due to, e.g., short and non-uniform water passages. This makes guarantee tests difficult to perform and in some cases it is even skipped.

The pressure-time method, also known as Gibson's method, was developed in the early 20th century, see Gibson [1]. It has, for a long time, been commercially used for site efficiency test due to its accuracy and, often, easy installation. Throughout the years there have been developments which have founded the specifications stated in an International Standard (IEC 41 [2]). The pressure-time method measures the discharge through pipes and conducts and is de facto an indirect method for site efficiency tests. The method is, roughly described, based on Newton's second law and uses the relation of the retarded mass of water and the corresponding pressure force that occurs during a rapid deceleration of the flow. By measuring the differential pressure force between two cross-sections and integrate over time it is possible to calculate the initial velocity from which the flow was retarded from, see equation 1.

$$Q = \frac{A}{\rho L}\int_0^t (\Delta P + \zeta)dt + q \quad [\mathrm{m^3/s}] \qquad (1)$$

The main, and well known, challenges of the method are according to the IEC 41 standard the limitation of the measuring length (the measuring length, L, must be over 10 m) and low initial velocities in combination of short measuring lengths (the velocity times the measuring length, UL, must exceed 50 $\mathrm{m^2/s}$).

This paper describes and presents results from a joint project between the Norwegian University of Science and Technology and Luleå University of Technology aiming to extend the pressure-time method to power plants where water passages (straight and homogenous pipes) available for measurements are too short to fulfill the criterions stated in IEC 41.
The project includes:

- Numerical analysis
    - Simulation of valve closure with corresponding pressure-time calculation
- Laboratory experiments
    - Measurements on straight pipes with variable L and UL
    - Sections enclosed with bends
    - Effects of sensor type
- Field tests to validate the laboratory results

LABORATORY EXPERIMENTS AND NUMERICAL SIMULATIONS

Experimental setup

The laboratory work is performed at the Water Power Laboratory at NTNU. The test rig used for this purpose consists of an open gravity driven pipe system with a maximum discharge of about 0.410 $\mathrm{m^3/s}$, see Figure 3. The available head for the system is 9.75 m (from the head level down to the measuring section). The test section consists of a 26.67 m stainless steel pipe with an internal diameter of 0.3 m. For the experiments with straight pipes, measurement sections are made at 11 positions along the test section. The first section is located 3.7 m upstream the valve and the 10 remaining sections at every meter further upstream. At each measuring section 4 pressure taps are mounted with 90 degree spacing around the circumference. A reference measuring section is positioned 20.7 m upstream the valve.

When a 90 degree double bend or a 45 degree double bend are inserted in the system the total length of the test section increases with 2.11 or 2.644 m, respectively. The downstream elbow is located 9.2 m upstream the gate valve, see Figure 3.

A hydraulic driven gate valve is used for the closing sequence. The closing time can be adjusted down to 2.5 s but it is kept around 4-5 s due to safety reasons. Repeatability of the closing time and effect of different times can be seen in Jonsson *et al* [3]. The initial discharge is adjusted with a throttle downstream the gate valve. A magnetic flow meter from Krohne (IFS 4000) is used as reference during all tests. It is calibrated with a weighing-time system and has an over all accuracy of 0.3%.

The tests are performed both with absolute and differential pressure sensors. The differential sensors used were Honeywell FP2000/FDW sensors. They have a range of ±0.5 bar and an accuracy of 0.25%. Totally 4 sensors are used; one at each position around the circumference. They are connected with plastic tubing which has an internal diameter of 6 mm and a length of 5 m. The absolute sensors used were Druck PTX 1830. They have a range from 0 to 5 bars and an accuracy of 0.1%. Totally 8 sensors are used; 4 at each measuring section, mounted directly on the pressure taps.

A 16 bit data acquisition system (Ni-6221) from National Instruments was used in the measurements. The sampling frequency was set to 2 kHz and the logging was performed without filtering.

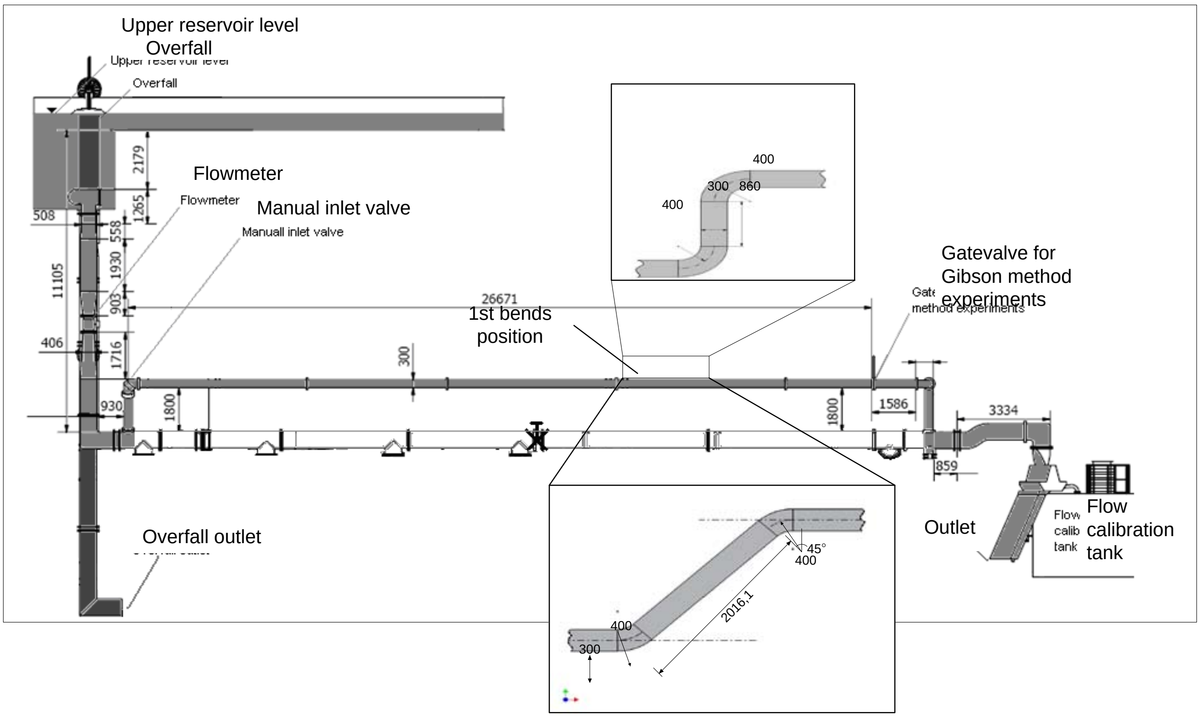

Figure 3: Schematic of the test rig at NTNU.

MEASUREMENTS

The measurements were performed at 4 different lengths; L=3, 6, 9 and 17 m for straight pipes and 4, 6, 9 and 20 m for the setup with bends. 3 discharges were chosen for the survey; $Q_1 \approx 0.4$, $Q_2 \approx 0.3$ and $Q_3 \approx 0.17$ m^3/s. With these measuring lengths and flow rates the UL relation can be varied from 10 to 100 m^2/s. This variation allows measurements inside and outside the criterions stated in the IEC 41 standard.

For the cases with bends the laboratory measurements were performed in 4 steps. First reference measurements with a straight pipe were performed. Thereafter tests with the two different sets of s-shaped pipes and at last reference measurements with a straight pipe were repeated. Double bends was chosen to amplify possible effects of the bend. There is a discussion whether the double bend will double or cancel out the effects of the bend, but until otherwise can be proved it is assumed that it will double the effects. Furthermore, it was most suitable due to installation reasons.

For more detail regarding the setup and measurement procedure, see Jonsson *et al* [3], Ramdal *et al* [4] and Ramdal *et al* [5].

NUMERICAL METHOD

Numerical simulations are made for comparison with laboratory experiments. A 1-dimensional Godunov type scheme called MUSCL-Hancock is used for the simulations, see Toro *et al* [6]. The transient friction is modeled with Brunone's model with Viskovsky formulation, see Bergant *et al* [7]. The test rig, from the head tank down to the test section, consists of bends, contractions and different pipe dimensions. Thus, the numerical model becomes complex if all parts are modeled. Therefore, the geometry is simplified with a straight pipe with an internal diameter of 0.3 m and a length of 40 m (approximately the length from the gate valve up to the head water level). The simulated pressures are thereafter used in pressure-time calculations, i.e., in the same way as in the experiments. See Jonsson *et al* [8] for more details regarding the numerical procedure.

FIELD TESTS

The field measurements were performed at the Anundsjoe power plant in Sweden. It has one Francis unit producing 5 MW at full load with a discharge of 10 m^3/s. The nominal head is 58.5 m and the water is delivered to the turbine through a vertical penstock. The penstock consists of a straight tube about 50 m long with an internal diameter of 2.2 m. Major part of the tube is in an accessible shaft allowing installation of pressure-time equipment. Its length allows also measurements according to the IEC 41 standard as well as outside the criterions. Figure 4 shows an overview of the power plant geometry with the instruments.

The measurements were performed with the same sensors as the laboratory experiments but since only 6 sensors were available for measurements, 3 sensors were used for each measuring length. Hence, the logging was simultaneously performed at both lengths. Pressure taps were mounted with 120 degrees around the circumference of the penstock. The sensors were connected to the taps with nylon hoses; internal diameter of 8 mm.

Two lengths were chosen; 7 and 30 m. The 30 m length was used for the efficiency test and as reference in the present survey. It satisfies the IEC 41 standard from around 65% load (UL>50). Since it was an efficiency test, the measurements were performed over the whole operational range and thus, many operational points were tested with the drawback of few repetitions. It had been preferable with fewer operational points with gain of more repetitions. Totally 19 tests were completed; from part load up to full load.

The results are presented in a similar way as the laboratory experiments but with the measurements at 30 m used as reference, see following equation:

$$e = \left(Q_7 - Q_{30}\right) / \left(Q_{30} + q\right) \qquad [-] \qquad (2)$$

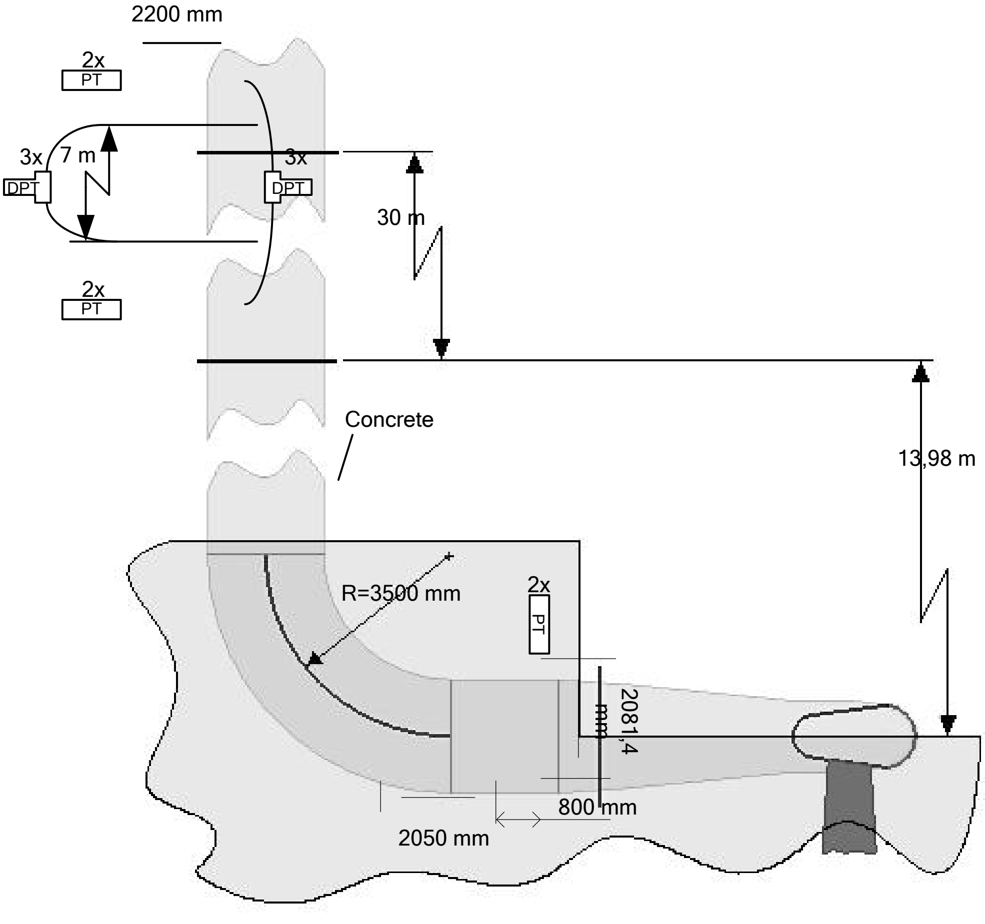

Figure 4: Anundsjoe power plant overview. (PT are absolute pressure transducers, DPT are differential pressure transducers)

Measurements with the bend were performed simultaneously with measurements in the pipe for L=30 m; the later is used as reference for analysis. Absolute pressure transducers were used instead of differential pressure transducers due to installation reasons. The transducers were mounted at the upper measurement cross-section and after the bend. The distance between the straight pipe measurement cross-section and the measurement cross-section after the bend is 47.938 m. Transducers were also placed at the down stream cross section used in the 30 m distance measurements. The pressure sensors used were Druck PTX 610 and Druck PTX 1830.

The pressure sensors downstream the bend did not have an optimal position since the spiral casing is close to the bend. This means the pressure taps had to be placed just downstream the bend; hence, it gives velocity and pressure distributions which ads uncertainty to the measurement. They also had to be placed 0.8 m into the converging pipe, which make need for compensation in the flow calculation equation in order to compensate for the small pressure difference the velocity difference cause. The fact that the bottom half of the pipe in front of the spiral casing is cast-in in concrete also gave limitation. The pressure transducers could only be mounted on the top half, giving uncertainty of the mean pressure. Further only two pressure transducers were installed. They were installed as close to the vertical middle of the pipe as far as the installation of the pressure taps allowed it.

The error for the bend measurements were calculated the same way as for L=7 m measurements with the measurements for L=30 m as reference.

RESULTS

Straight pipe with short distance between measurement cross sections

The results from the numerical simulations and laboratory experiments are presented as deviation in percent from the reference (magnetic flow meter). Each value from the laboratory tests are mean values taken from 18 runs for the differential sensors and 6 to 12 runs from the absolute sensors. The results from the field measurements are presented in a similar way but with the measurements for L=30 m as reference value.

Two main criterions in the IEC 41 are the limits of the measuring length (L>10 m) and the UL relation (UL>50 m^2/s). Figure 5 and Figure 6 shows results from measurements outside these limitations. For the absolute sensors (Figure 6) reference measurements at 17 m (UL≈40 to 100 m^2/s) were performed for comparison. It can be seen that both the numerical and experimental results follow a similar pattern with a slight difference in magnitude. For both the absolute and differential sensors, the error deviates more from the numerical results with decreasing length. The difference in mean values is similar between both types of sensors but the spread at each measuring length is larger for the absolute sensors, especially for short lengths, see

The presented results are extended measurements from the one presented in Jonsson *et al* [3], where only one absolute sensor was used at each measuring section. This sensor was connected to the 4 pressure taps with plastic tubing and through a manifold. That configuration gives much larger discrepancy of the mean value compared to the numerical for short lengths and low velocities, cf. Figure 8(a) in Jonsson *et al* [3].

Table 1. Hence, those sensors get a larger relative error compared to the differential sensors.

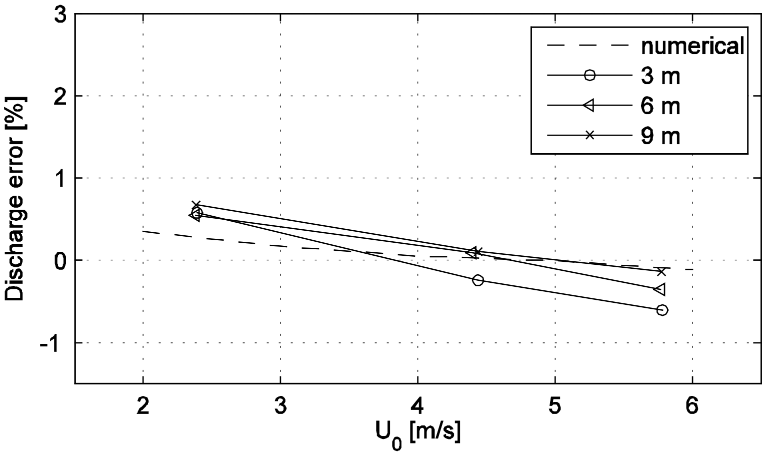

Figure 5: Experimental and numerical flow error with differential pressure sensors at measuring length 3, 6 and 9 m.

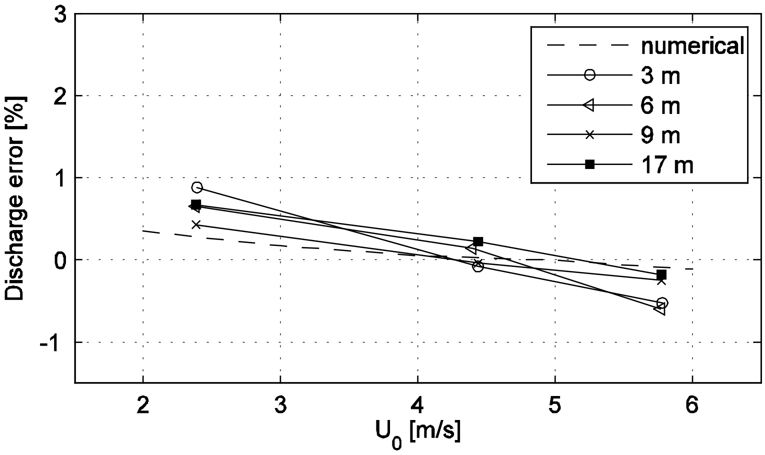

Figure 6: Experimental and numerical flow error with absolute pressure sensors at measuring length 3, 6, 9 and 17 m.

The presented results are extended measurements from the one presented in Jonsson *et al* [3], where only one absolute sensor was used at each measuring section. This sensor was connected to the 4 pressure taps with plastic tubing and through a manifold. That configuration gives much larger discrepancy of the mean value compared to the numerical for short lengths and low velocities, cf. Figure 8(a) in Jonsson *et al* [3].

Table 1: One standard deviation of the discharge error for each sensor type and measuring length.

Measuring length [m]	3	6	9	17
Differential sensors [%]	0.57	0.31	0.16	-
Absolute sensors [%]	1.03	0.55	0.24	0.26

Figure 7 presents the discharge error calculated from measurements performed at L=7 m (8<UL<19) relative to the one performed at L=30 m (36<UL<68). The error is plotted versus the guide vane opening where 100% is the opening of the highest tested discharge. The difference between the errors at the two measuring lengths never exceeds 1%. The error follows a random pattern and no U dependency can be found. Furthermore, measurements at the length of 30 m follow the IEC 41 standard and should be rather accurate. However, the discrepancies in the measurements are originated in both, and to find the magnitude an accurate reference measurement is needed.

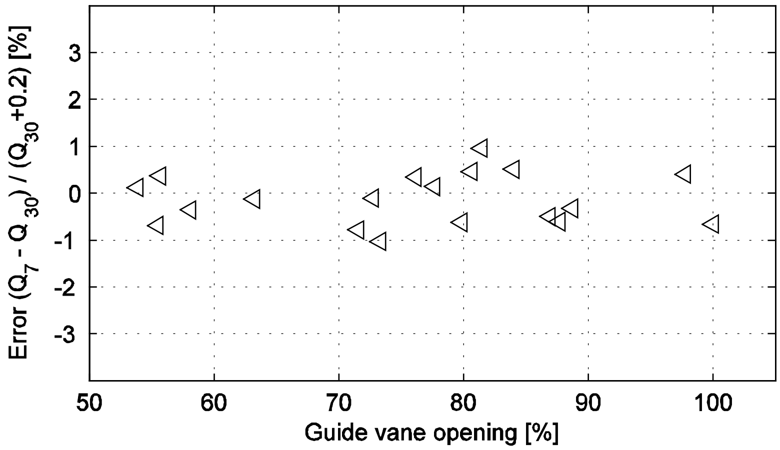

Figure 7: Difference between measured discharge for L=7 and 30 m at the Anundsjoe power plant, Sweden.

MEASUREMENTS WITH BEND

Figure 8 shows the differences in the calculated mean values for the cases 2x90 degrees and 2x45 degrees bends versus the straight pipe reference. There is a 0.9% underestimation in the flow calculated with 2x90 degree bends compared to the straight pipe reference. The results for the 2x45 degree bends gave approximately the same result as the straight pipe. For both cases, the difference is found nearly constant, and independent of flow velocity. Furthermore, the spread for both cases are in the same range as for straight pipe, see Table 2. It can also be seen that the bend angle is an important parameter for the result.

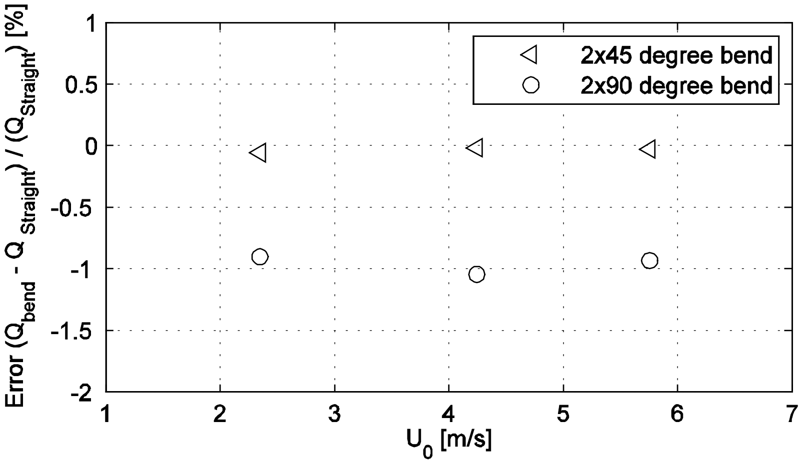

Figure 8: Differences between measurements with straight reference and measurements with bends.

Table 2: One standard deviation of the mean for each setup (bend) and length.

Measuring length [m]	4/3.7	6/5.7	9/8.7	18.7/20
2x90 degree [%]	0.27	0.29	0.22	0.23
2x45 degree [%]	0.43	0.31	0.30	0.33

For the field test there was also an underestimation of the flow when having a bend between the measurement cross-sections. The measured test points and the difference between the bend measurements and the reference are presented in Figure 9. Considering measurement uncertainties and spread of the results, the difference seems also to be constant at approximately -8%, and thus independent of U.

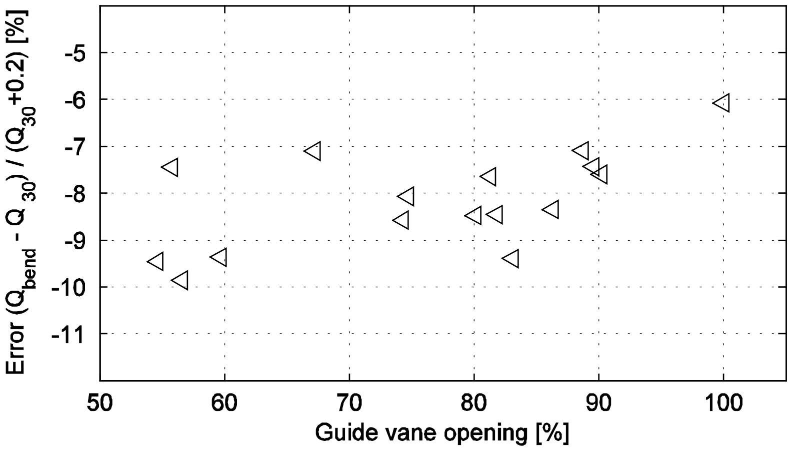

Figure 9: Differences between measurements with straight reference and measurements with bend.

How relative differences in the geometry for the field measurement compared to the laboratory measurements affects the result can as for now not be explained. The differences are for the field measurements mainly compared to the laboratory:

- larger pipe diameter
- larger bend radius relative to pipe diameter
- only one 90 degree bend
- pressure transducer placement
- geometrical perturbation downstream the measuring cross-section

A last parameter which can cause differences is the position of measurement cross sections relative to the bend and pipe diameter. Secondary flows and skewed flow velocity distribution in the pipe can be of significance for the calculated result.

More detailed analysis on bends within pressure-time measurements can be found in Ramdal *et al* 0

DISCUSSION AND CONCLUSIONS

The numerical and laboratory, when L>6 m, results show an increasing error with decreasing flow rate. For L=3 and 6 m the flow is under estimated for the highest discharge. Since measurements have been made with only one pipe diameter it is not possible to conclude if it is purely velocity or Reynolds number dependent. This behavior may arise from the transient friction during the valve closure. In the pressure-time method the friction is treated as quasi-steady with a friction factor obtained from the initial state and thereafter used during the whole integration. Transient friction during deceleration is complex and only empirical or semi empirical expressions exist. However, in the numerical case the differential pressure is obtained with simulations of a valve closure where the friction is treated as transient with Brunone model. It is then integrated back with pressure-time method that uses quasi steady friction. Thus, this loop may induce the difference between the initial and the pressure-time integrated flow. By implementing transient friction in the pressure-time method it may be possible to reduce this error. Even though it is small in the numerical results compared to the experimental ones, it may give good results for the experimental as well. A more detailed numerical analysis of the above mentioned behavior may point out its origin and velocity/Reynolds number dependency.

The laboratory results show that it is possible, under certain conditions, to use the pressure-time method at lower L and UL than stated in the IEC 41 Standard. The results from the field test shows that the flow difference obtained with a long and short length is below 1% for all cases. The error is randomly distributed and has a mean of -0.1%. If for L=30 m, measurements are treated as a precise reference, the short measurements will have results within the limit in the standard.

Both field and laboratory measurements with bend(s) between the measurement cross-sections have proved to give a constant and water velocity independent underestimation of the flow. However, the laboratory measurements had a much smaller difference compared to the field tests. In the laboratory tests, 2x45 degree bends had almost no difference compared to the reference measurements, while the difference was significant with 2x90 degree bends. Such results support the hypothesis that 2 bends may compensate for each other. How different parameters, such as pipe diameter, bend angle and bend radius affect the result of the calculations are topics of interest in future research. It is a goal to get a systematic compensation for the under estimation based on these parameters. Also the measurement cross-sections distance from the bend, and how this affects due to secondary flows and skewed velocity profiles is not known.

Finally, more field measurements are necessary and will be performed at a power plant where a permanent ultrasonic system is installed. Even though the accuracy of that equipment are in discussion, it will hopefully, give some answers to questions that have been arisen throughout this work.

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NOMENCLATURE

A	Cross-sectional area of the pipe	[m^2]
L	Measuring length	[m]
U	Initial velocity	[m/s]
Q	Discharge	[m^3/s]
ΔP	Differential pressure	[Pa]
q	Leakage flow	[m^3/s]
ζ	Pressure losses	[Pa]
ρ	Water density	[kg/m^3]

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