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Comparison of discharge measurements - Thermodynamic to US Clamp-On, stationary US and Needle Opening Curve

Tobias Rau, Marco Eissner

Voith Hydro Holding GmbH & Co. KG
Alexanderstr. 11, 89522 Heidenheim, GERMANY

Abstract

For high head hydro turbines the thermodynamic method is the most common way to measure the efficiency. This method uses the conversion of energy and enables to derive the discharge from its results. Other methods measure the discharge directly to verify the turbine efficiency at a hydroelectric unit.

According to the IEC code 60041 the thermodynamic method is a primary method and therefore it will be taken as a reference in this paper for the comparison with three other methods of discharge measurement: a stationary ultrasonic device installed in front of the spherical valve and an ultrasonic clamp-on system between spherical valve and distributor inlet. In addition the needle opening of the six nozzles are used for the determination of the discharge.

All the measurement methods are performed at a six nozzle vertical Pelton turbine with a head of approximately 500m. Thus every measurement method has the same boundary conditions and can be compared with each other.

All the described methods, compared with the thermodynamic method, are according to IEC code 60041 secondary methods and can be used only for relative efficiency tests. The results of this test show besides the accuracy of these methods also their limitations.

Partly the results correlate very well with those of the thermodynamic method. The ultrasonic clamp-on system had higher deviations mainly in the lower load part, maybe caused by a not optimal measuring position. The data of the stationary ultrasonic and the needle opening are very similar in comparison to the primary method.

1 Introduction

Finding solutions of doing more cost effective relative efficiency tests it becomes essential to acquire more experience with different kind of discharge measurements. Especially compared to absolute methods accepted by IEC code 60041, e.g. the thermodynamic method.
Within the last years the technical progress comes up to a point, where it is possible to measure discharges quickly with clamp on devices for temporarily installation.

This paper shall give a better understanding and shall spread the experience made with different kind of discharge measurement techniques and shall also show their limitations of use by comparing these results to the results of a thermodynamic efficiency test.
In this paper the results of the thermodynamic efficiency test shall be the reference to all other methods which are described and applied.

2 Theoretical background

2.1 Thermodynamic

The thermodynamic method results from the application of the conversation of energy. It is a transfer of energy between the machine and the water passing through it. The hydraulic efficiency (equation 4) of a turbine is defined as the ratio between the specific mechanical energy (equation 1) and the specific hydraulic energy (equation 2).

This method gives the possibility to determine directly the energy that the water transmits to the turbine shaft. Beginning from the inlet reference section derived from the measured quantities and from the thermodynamic properties of water. This energy is called specific mechanical energy. The specific mechanical energy´s unit is Joule per kg water.
To measure all necessary quantities in practice a small portion of water will be extracted out of the main flow of the turbine into so called vessels.
For the application of the thermodynamic method three different procedures can be used:

- Full expanded fluid (pressure term disappear)
- Partial expanded fluid (temperature term disappear)
- Not expanded fluid (measured quantities similar to the values in the main flow)

These days the method of full expansion and partial expansion usually is not used any more.

$$E_m = \bar{a} * (p_{11} - p_{21}) + c_p * \Delta T + \frac{v_{11}^2 - v_{21}^2}{2} + \bar{g} * (z_{11} - z_{21}) [J/Kg]$$

equation 1 General definition of specific mechanical energy

$$E = \frac{p_1 - p_2}{\rho} + \frac{v_1^2 - v_2^2}{2} + g * (z_1 - z_2) [J/Kg]$$

equation 2 General definition of specific hydraulic energy

$$H = E / g [m]$$

equation 3 Net head

$$\eta_h = \frac{E_m}{E} [\%]$$

equation 4 Hydraulic efficiency

where

a	isothermal factor of water
p_{11}	pressure in the vessel on the high pressure side
p_{21}	pressure in the vessel on the low pressure side

cp	the specific heat capacity of water
ΔT	the differential temperature between high and low pressure side
v_{11}	the velocity in the vessel on the high pressure side
v_{21}	the velocity in the vessel on the low pressure side
g	the acceleration due to gravity
z_{11}	the level of the vessel on the high pressure side
z_{21}	the level of the vessel on the low pressure side
p_1	the pressure in the reference section on the high pressure side
p_2	the pressure in the reference section on the low pressure side
ρ	the density of water
v_1	the velocity in the reference section on the high pressure side
v_2	the velocity in the reference section on the low pressure side
z_1	the level of the reference section on the high pressure side
z_2	the level of the reference section on the low pressure side

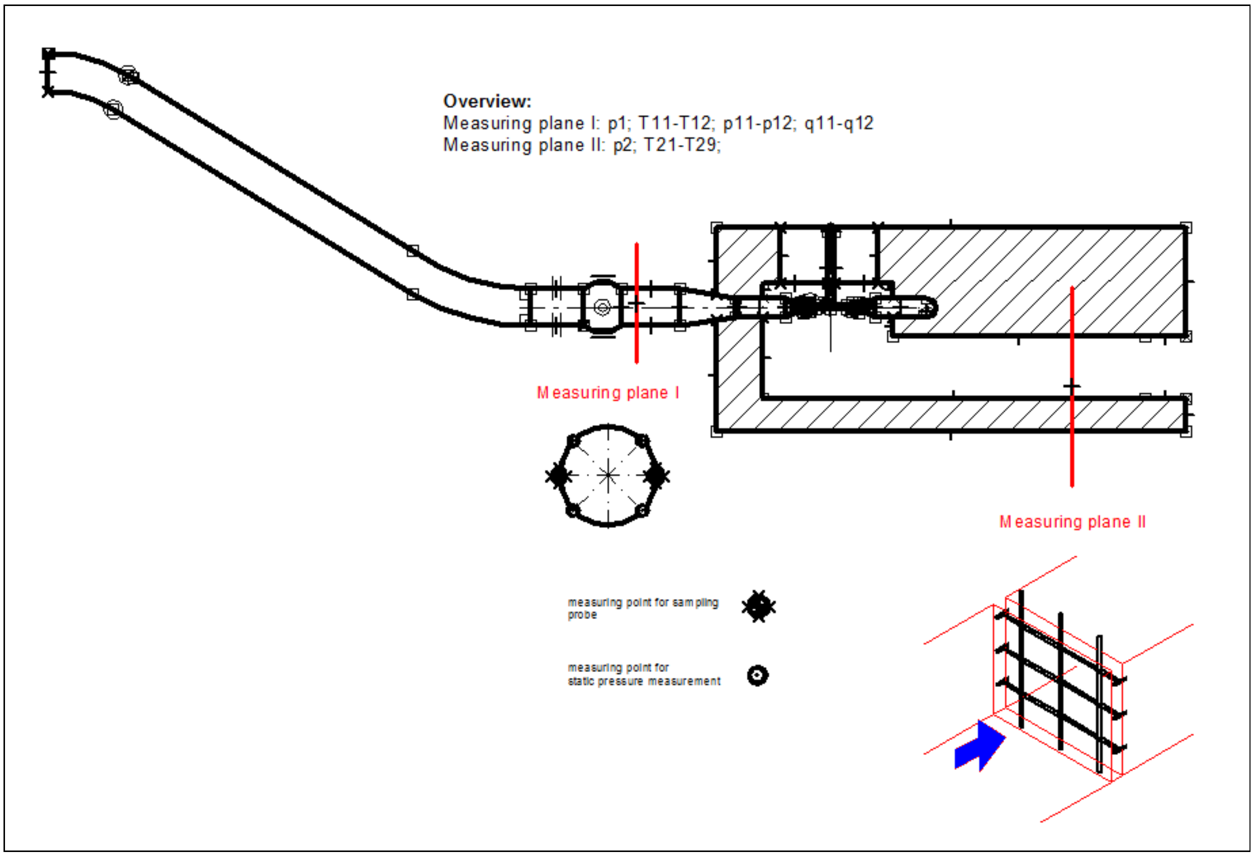

Figure 1 Schematic arrangement of measuring points for the thermodynamic method

Figure 1 shows the schematic arrangement of the measuring points for the thermodynamic method at a vertical Pelton machine which was applied for this comparison. On the high pressure side the water was extracted with two sampling probes and taken into vessels. In both vessels the pressure, the temperature and the amount of extracted water was measured separately for the determination of the specific mechanical energy. In the penstock at high pressure side the inlet pressure was measured as an average of four pressure taps.

On the low pressure side a measuring frame was installed with nine temperature sensors and two level probes. With this set up the energy distribution can be determined with a good resolution and accuracy. The measuring frame was installed in a distance of app. 8 x D that means the minimum distance recommended by IEC60041 was met.

By indirect determination of the mechanical power and the determination of specific mechanic energy the discharge through the machine can be calculated.

2.2 Stationary Ultrasonic System

The acoustic method of discharge measurement (ultrasonic, time of flight or transit time) is predicated on the propagation of velocity of an acoustic signal and the main flow velocity is vectorial summed. An acoustic signal sent downstream travels at a faster absolute velocity than an acoustic signal sent upstream. By measuring the travel times in both directions it is possible to determine the average axial velocity of the acoustic path crossing a certain cross section.

$$Q = \frac{D}{2} \sum_{i=1}^{n} w_i * \bar{v}_{axi} * L_{wi} * \sin\varphi$$

equation 5 General equation for discharge according to transit time method [1]

where

D	penstock diameter
L_{wi}	the length of the acoustic path
w_i	the weighting coefficients
v_{axi}	the averaged axial flow velocity
n	the number of acoustic paths in one plane
φ	the angle of the acoustic paths

The stationary ultrasonic system was installed to detect the leakage in the penstock (see figure 2), e.g. in case of penstock rupture. It measures continuously the flow rate in the 2 penstocks and in the 4 inlet pipes to each turbine. Each penstock and the two corresponding inlet pipes will be compared continuously. The flow rates are measured with an ultrasonic transit-time measurement device on each line. For the comparison test the result of the section before the main inlet valve was used to measure the discharge by acoustic transit time method. The scope of this installation was not the measurement of efficiencies or performance guarantees.

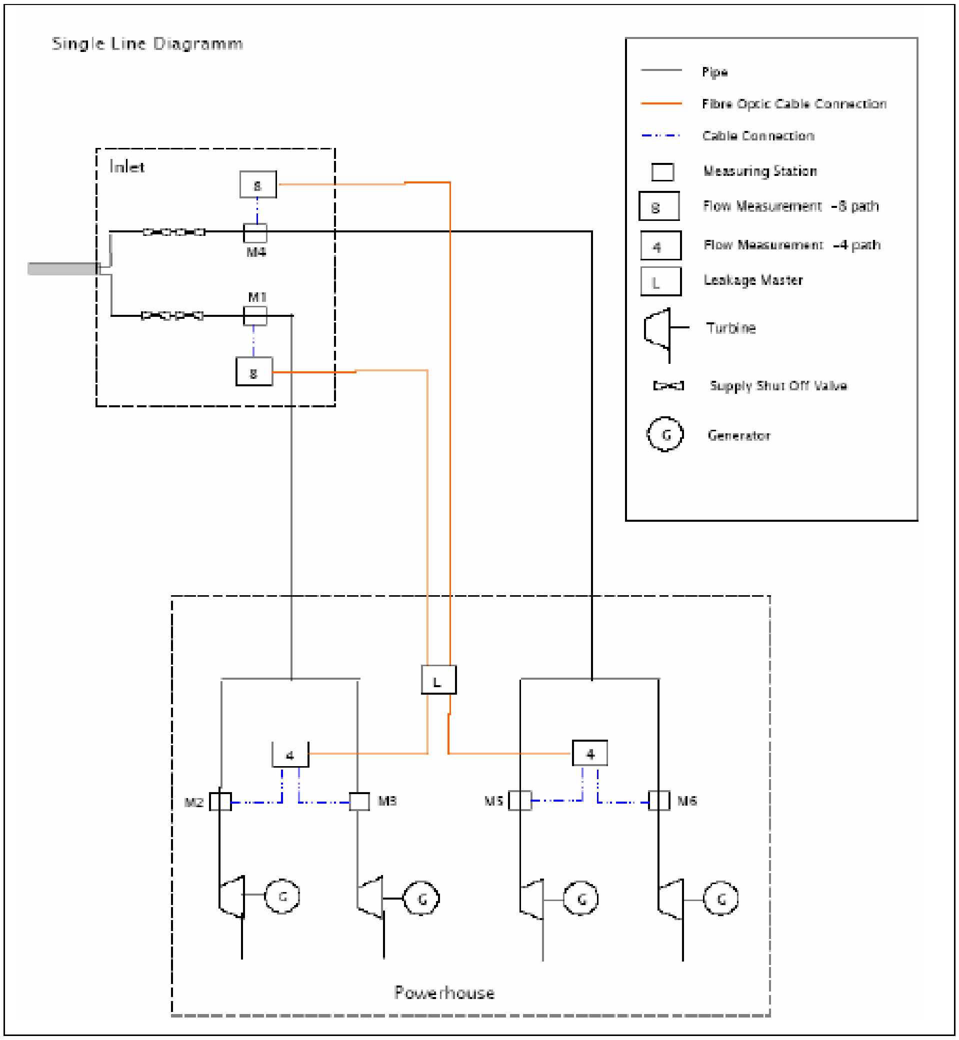

Figure 2 Single Line Diagram of leakage monitoring [2]

Figure 3 shows the arrangement of the acoustic paths before main inlet valve. In general the arrangement is dependent on the flow profile and the pipe diameter. For this project an arrangement of four planes with four paths was installed.

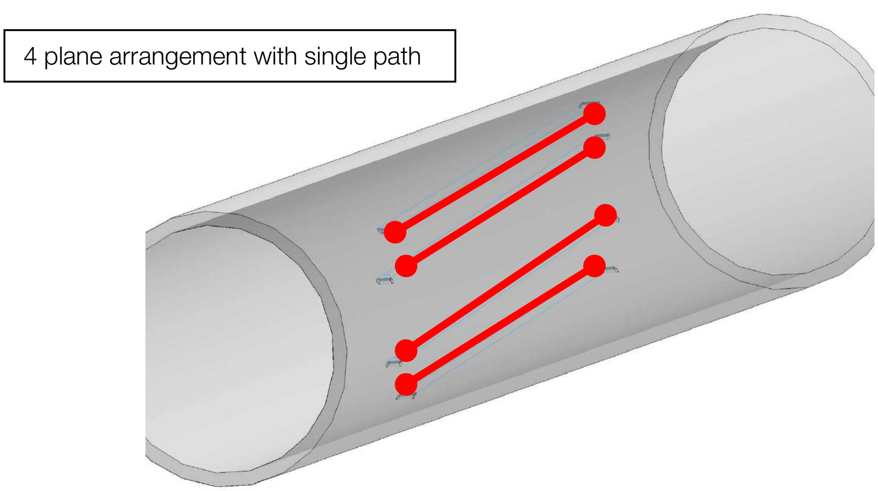

Figure 3 Arrangement of acoustic paths (US stationary)

2.3 Clamp-On Ultrasonic System

The principle of the US Clamp-On system is the same like described in 2.2 Stationary U. An acoustic pulse which is sent upstream travels at a lower absolute speed than an acoustic pulse sent downstream. The average axial velocity of the fluid crossing the path of the pulses is determined by measuring the travel times of the acoustic signal sent in the two directions. Major different to the stationary system is that each path for the clamp-on device travels through the center of the penstock cross section (refer to figure 4). That means the determination of the velocity profile corresponding to the stationary US-device is not possible.
For the comparison test it was chosen a one plane arrangement with single path. The choice of the measuring position was limited by accessibility to the penstock. Therefore the measuring section was selected directly after the main inlet valve (MIV) near to the distributor inlet. The conditions for this arrangement were not good because the measuring section was in a conical part of the penstock and the outlet of the measuring sections was only in a distance of app. 1xD to the distributor inlet.

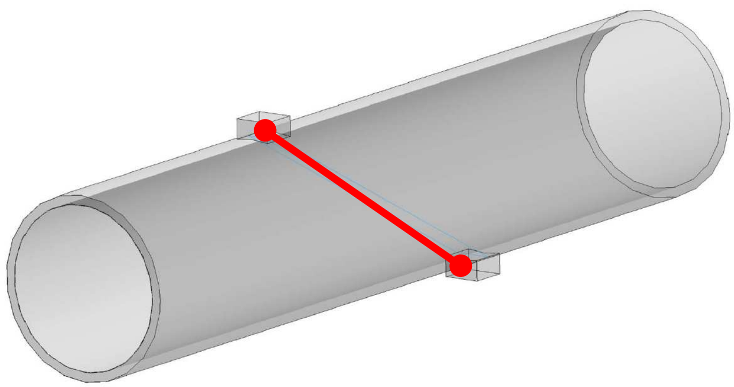

Figure 4 Arrangement of acoustic path (US clamp on)

2.4 Needle Opening

The flow through the machine can be determined with the needle opening curve as well. The net head and the cross section of the needle opening depend on the needle stroke. The net head results from the determination of the specific hydraulic energy (refer to equation 2 and equation 3) and the needle stroke can be measured directly with any kind of linkage sensor. With the needle stroke the needle cross section can be determined.
To achieve an accurate needle opening curve a tested model is beneficial. The results and experience can be adopted to the prototype and the standard flow function can be adjusted. Of course the accuracy is also depending on the deviation between theoretical design of the needle and the manufactured needle at the prototype. That means the more the analogy from design to prototype is fulfilled the merrier is the accuracy of this kind of discharge determination.

$$w = 0{,}98 * \sqrt{2 * g * H}$$

equation 6 Standard flow function with loss factor

$$Q = A * w$$

equation 7 Discharge

3 Comparison of discharge values

Results of all methods were compared to the results of the thermodynamic efficiency test. Deviations between the different methods and the results of the thermodynamic efficiency test were determined.

The results show clearly that the measurement with the clamp on system has significant deviations to the reference measurement. There are several reasons why the deviations are higher than expected compared to the reference. The clamp on system was installed in a slightly conical part of the penstock. This matter did not account for a higher accuracy but does not explain such high deviations. Additionally the system was installed very close to the distributor inlet (because of accessibility to the penstock) were the flow distribution can change keenly when at lower loads not all nozzles are opened. With just one path an adequate determination of the flow velocities over the cross section is not possible especially if there is a highly disturbed flow pattern. With the results achieved from the clamp on system it was not possible to derive a reasonable index test curve because the deviations were not constant and even changed their prefix.

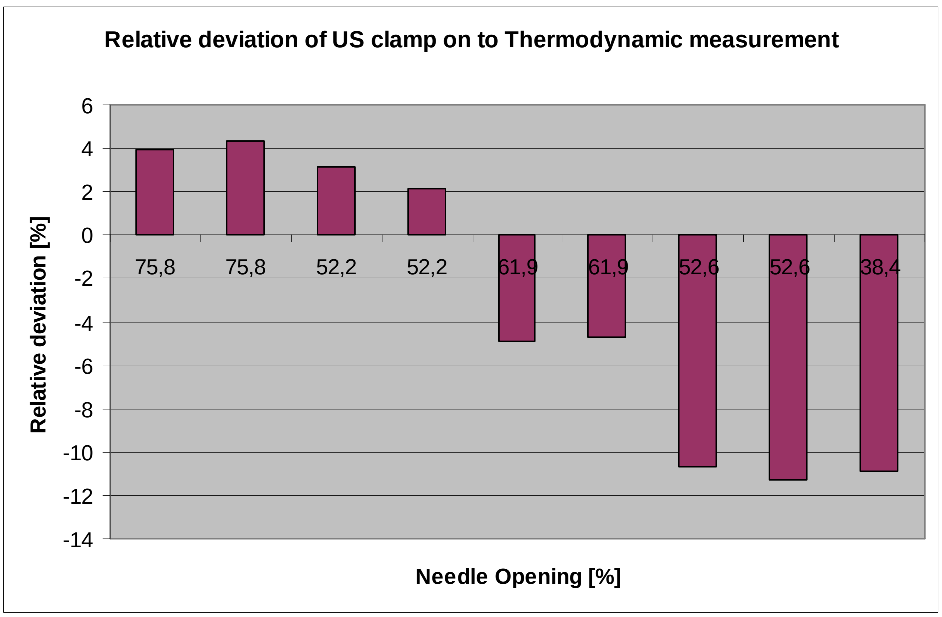

Figure 5 Relative deviation of US clamp on to reference measurement

The deviations of the stationary ultrasonic system to the reference measurement are in an acceptable range if you consider that it is a four planes system with single paths arrangement. The deviations of the stationary ultrasonic system are all below 1%. Except of one outlier all deviations have the same prefix and are all in the same magnitude. With values achieved from the stationary ultrasonic device it was possible to reproduce the shape of the efficiency curve according to the results of the reference measurement. For index testing the device deliver acceptable results.

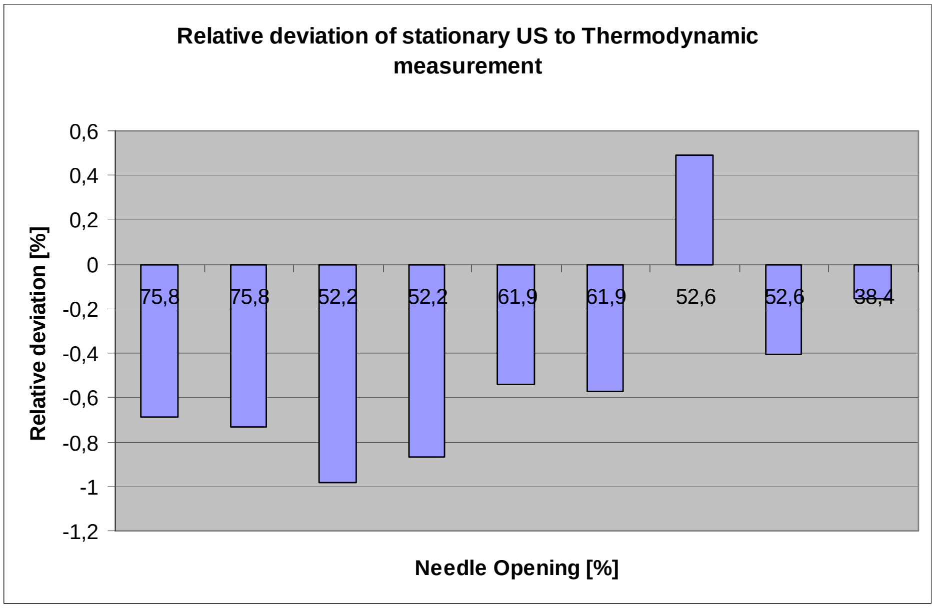

Figure 6 Relative deviation of stationary US to reference measurement

The deviations of the needle curve discharge are all below 0.9%. The deviations have all the same prefix and are roughly in the same magnitude. The deviations getting higher to smaller loads of the unit that means in the 2 and 3 nozzle operation of the machine the deviations are higher compared to the reference measurement. With values achieved from the needle curve it was possible to reproduce the shape of the efficiency curve according to the results of the reference measurement. For index testing this method deliver acceptable results.

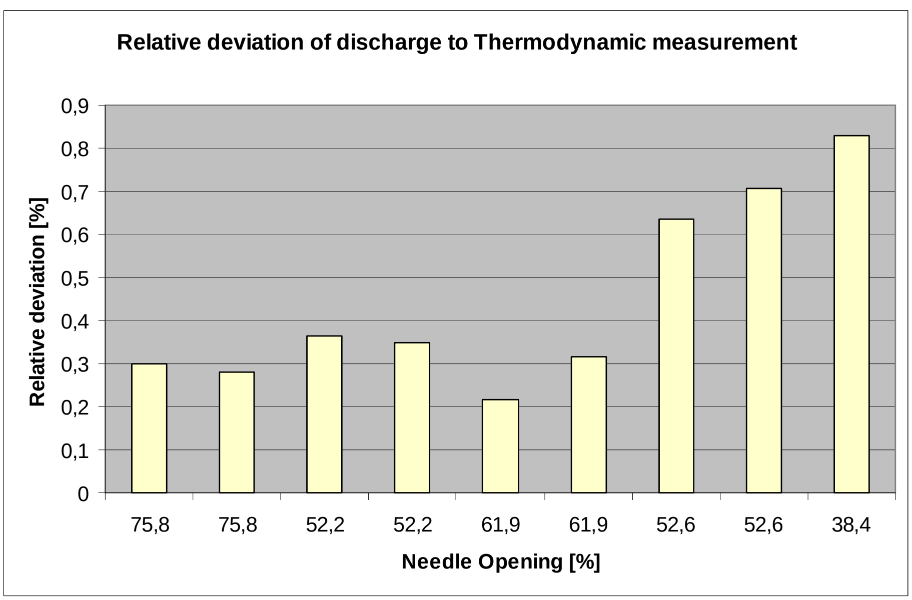

Figure 7 Relative deviation of discharge to reference measurement

4 Summary

The results of this comparison show explicit that the choice of the measuring method, the measuring section and the measuring arrangement has to be carefully chosen according the aim of the respective measurement. Furthermore a detailed validation of the test results and the conducted test setup is essential.

Especially for the ultrasonic clamp-on discharge measurement special care has to be taken to achieve reasonable results. The general statement that a clamp on device can be easily installed without focus on the right position and setup cannot be confirmed based on the results of this comparison. Contrariwise good measuring conditions are more important to achieve reasonable values.

The four plane single path stationary ultrasonic device achieved reasonable results without any correction. This experience confirms that for Index tests ultrasonic devices with a smaller amount of paths can be used properly and without special focus on the borderlines of the measuring setup. For the use at absolute efficiency tests it is strongly recommended to use at least a 4 planes 8 paths system to achieve the necessary accuracy. Otherwise special care has to be taken to measuring set up and the flow distribution (e.g. by CFD).

The results of the needle opening curve give quiet good results. Especially if you consider that the effort for this measurement is quiet small. At a Pelton machine just the measurement of the inlet pressure, the electrical power and the needle opening is necessary to achieve an efficiency curve. Even if you don’t achieve absolute efficiencies by this method it is a cost effective measurement for Index testing. In this comparison the results agree quiet well to the reference measurement.

5 List of references

[1] IEC, Bureau Central de la CEI (1991): International Code for the Field Acceptance Tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump turbines, *Publication 41*, third edition, Genève

[2] Systec Controls GmbH (2007): Operations and Maintenance Manual of Combined Water loss Detection and Flow Measurement System, Puchheim