Accuracy of clamp on ultrasonic measurement based on thermodynamic efficiency measurement, a case study

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1 General Description

Within the framework of a measurement campaign in one of Austria's largest storage power plants, the HPP Kaunertal, it was possible to simultaneously apply two frequently used and recently much-discussed measurement methods. In the hydropower plant, 5 tandem Pelton turbines with 2 nozzles per runner located on both sides of the generator are operated. The data of the power plant is summarized in Table 1. The cavern power plant is entirely underground including the area of the distribution pipeline, which is an excellent advantage for the thermodynamic efficiency measurement, as the influence of solar radiation is minimized. The headrace tunnel has a total length of L = 14100 m and a maximum nominal diameter of 4000 mm.

TABLE 1: DATA HPP KAUNERTAL

Manufacturer turbine / generator	VOITH / Siemens, refurb. Andritz
Type of Pelton turbine	2-nozzle, tandem
Head, net	810 [m]
Discharge (per unit)	9,6 [m³/s]
Nominal power (per unit)	83,5 [MW]
Rotational speed	500 [rpm]
Max. jet diameter	165 [mm]
Nominal diameter	2310 [mm]

The Gepatsch reservoir is the headwater of the Kaunertal power plant; it is located at a height of 1660 m and has a usable capacity of 139 million m³. The annual production is about 661 GWh with a nominal installed power of P = 392 MW (depends on the water level in the reservoir). The maximum gross head is 895 m and was kept almost constant during the measurement (maximum deviation: 1%). Machine unit 5 was commissioned in 1964 and accepted in 1965, employing thermodynamic measurements. Precisely this unit has been measured during the campaign after refurbishment presented herein (Figure 1)

The thermodynamic measurements of one partial turbine of a machine set were carried out within 12 h with a total of 13 measuring points and up to the peak power of 41.5 MW (one partial turbine). In total, power generation was interrupted for only 2 hours. In order to ensure reliable measurement results and reproducibility, the specific hydraulic energy was measured twice and the specific mechanical energy three times per operating point, whereas previously defined operating points were repeatedly approached. A stationary operating state could be ensured by waiting for the surge tank oscillations after setting an operating point. In addition, the environmental parameters such as relative humidity, room temperature, air admission and the heat input into the measuring chamber between the individual operating points were recorded during the measurement according to the IEC standard [1].

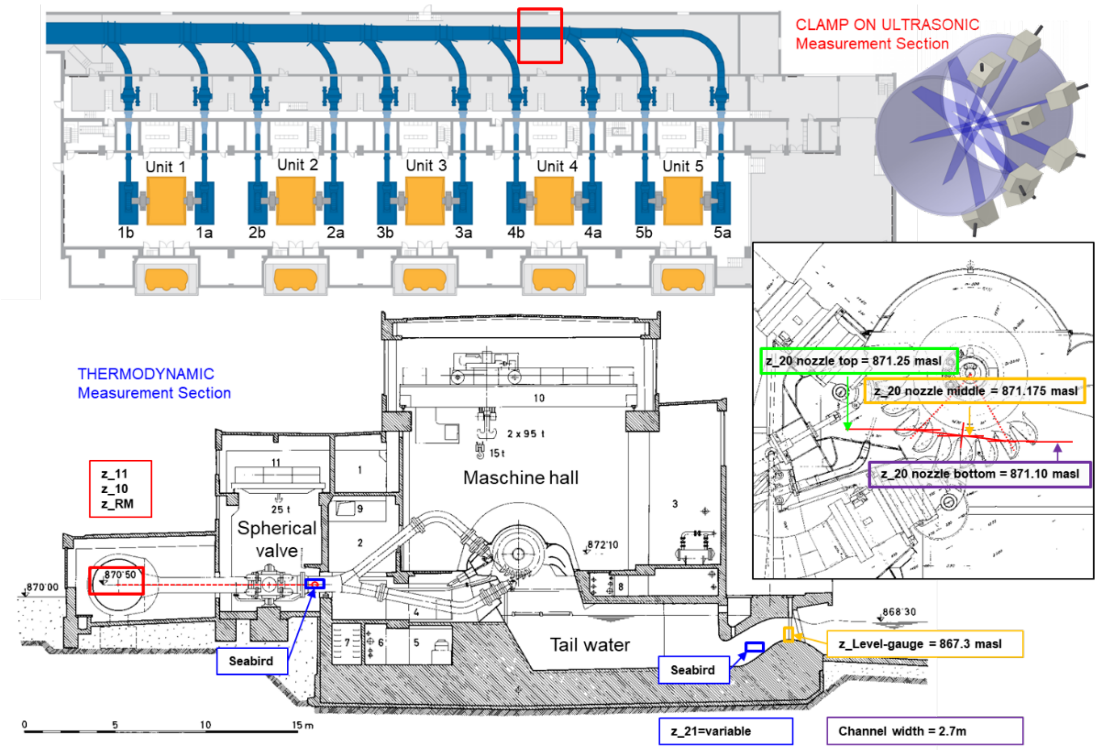

FIGURE 1: POWER PLANT MEASUREMENT SECTION, OVERVIEW

2 Measuring arrangement and measuring equipment

According to the IEC standard, the acquisition of the temperature distribution in the tailwater was realized with two temperature sensors $T_{21\text{-}1}$ and $T_{21\text{-}2}$ over the cross-section. The necessary positioning of the temperature sensors depending on the operating point and thus the tailwater level (Figure 2) was achieved by a steel frame construction in the area of the dam beam, which was height-adjustable. The measurement sensors applied are listed in Table 2. This setup enabled six measuring points to be realized at three different height levels. As the height level was not constant during the measurement campaign, a dynamic adjustment of the levels was used. The measurement uncertainty for the efficiency of the thermodynamic measurement campaign as reference value was calculated to 0.435% and 0.601% depending on the operating point. According to the IEC standard [1], both systematic and random errors were considered.

All measured values were registered with a particular, customized measurement system based on a National Instruments CompactRIO. The cRIO is a resilient embedded system allowing for user configuration, comprising a real-time operating system, a user-programmable logical grid area and holds up exchangeable input/output modules. The system's measurement software – which has been uniquely tailored to meet the requirements of the efficiency measurements – allows for the analysis of the raw measurement signals and subsequently also for the complete allocation and direct presentation of the measurement results (without correction terms), which have to be realized during the measurement campaign. Figure 3 shows the installation of the Acoustic Transit Time measurement equipment. As the measurement section, a straight part of the distribution pipe between unit 4A and unit 4B was chosen.

TABLE 2: MEASUREMENT EQUIPMENT

Upstream and downstream temperature measurement	
Seabird SBE 3	
Measuring range	-5°C bis +35°C
Accuracy	± 0.001°C
Long-term stability	0.002°C/a
Self-heating	<0.0001°C
Source signal	± 0.5 V rectangular signal
Frequency range	3-5 kHz
Upstream pressure measurement	
Rosemount PG5 pressure sensor 3051	
Max. measuring range	2000 PSI / 138 bar
Reference accuracy	± 0.04% of limit of measuring range
Total accuracy	± 0.12% of limit of measuring range
Long-term stability	0.1%
Output signal	4-20 mA
Measurement rate	22 Hz
Downstream pressure measurement	
Siemens SiTrans P-Series MPS	
Measuring range	0-10 *mWC*
Accuracy	± 0.3% of the upper range value
Long-term stability	0.2% of the upper range per year
Output signal	4-20 mA
Acoustic Transit Time measurement System	
Flexim Fluxus, 706, 4 Channel	
Sensor type	Shear wave -type
Sensor frequency	0.5MHz
Diameter range	100-6500mm
Flow velocity range	0.01-25 m/s
Measurement uncertainty	±1% of reading ±0.005 m/s
Repeatability	0.15% of reading ±0.005 m/s

The ultrasonic flow rate measurement equipment consists of a state-of-the-art stationary transmitter and 8 transducers building up 4 independent measuring paths. The system was modified to use the transmitter as a compact mobile clamp on system with high measurement accuracy (see Figure 3 (c)). The shear wave type sensors are mounted on the outside of the pipe with the help of tension belts clamping a rectangular frame on the pipe for each transducer. Each pair of sensors was mounted on the same side of the pipe. This technique allows for an effortless alignment of the sensors along a straight line. The ultrasonic waves are reflected on the opposite inner wall of the pipe, and the measured value is directly averaged with each subsequent passage. The number of passages is only limited by the maximum excitation of the ultrasonic transducers, the quality of the reflection of the waves and the length of the useable measuring section. This results in an even number of acoustic passages through the water. The so-called “V” arrangement with two passages and one reflection was used for the actual measurement campaign for all four sensor pairs. The installation shall never be directly on the top or bottom point of the pipe to keep air bubbles and fouling away from disturbing the acoustic waves and the reflection of the waves on the inner surfaces. The mounting positions have been chosen to be 11, 10, 8 and 7 o'clock starting with 12 o'clock on the top of the pipe while looking in downstream direction. (see Figure 3 (b)).

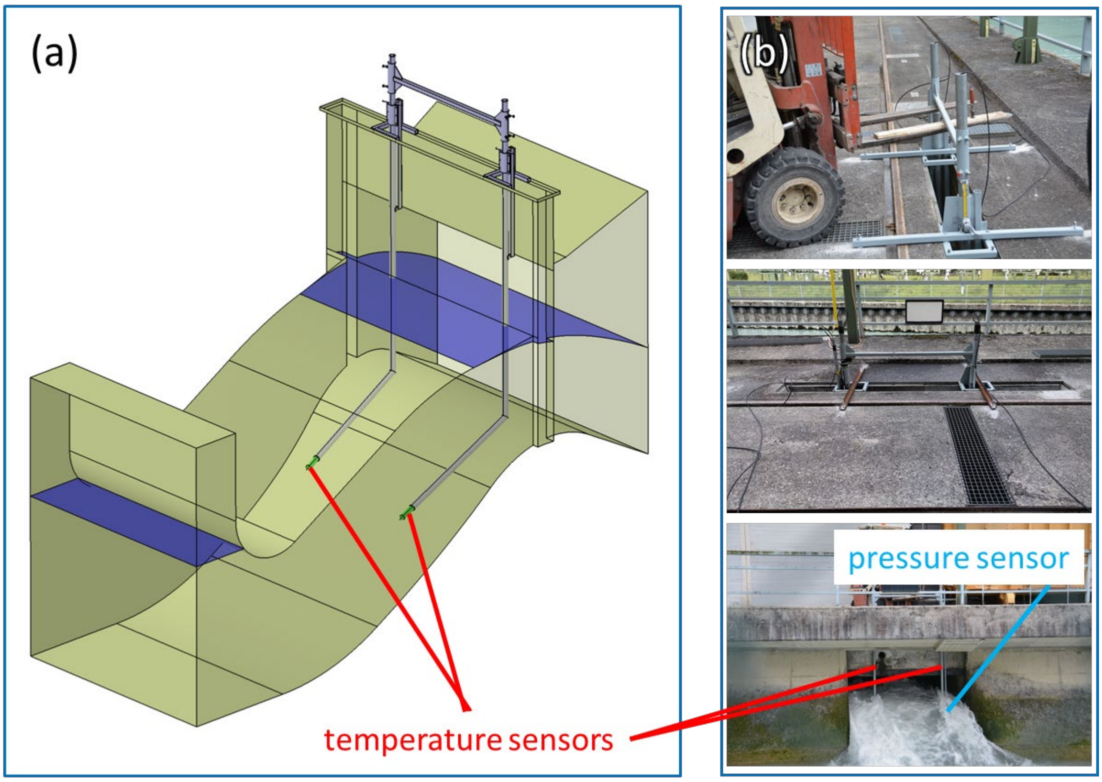

FIGURE 2: TAILWATER MEASUREMENT SECTION

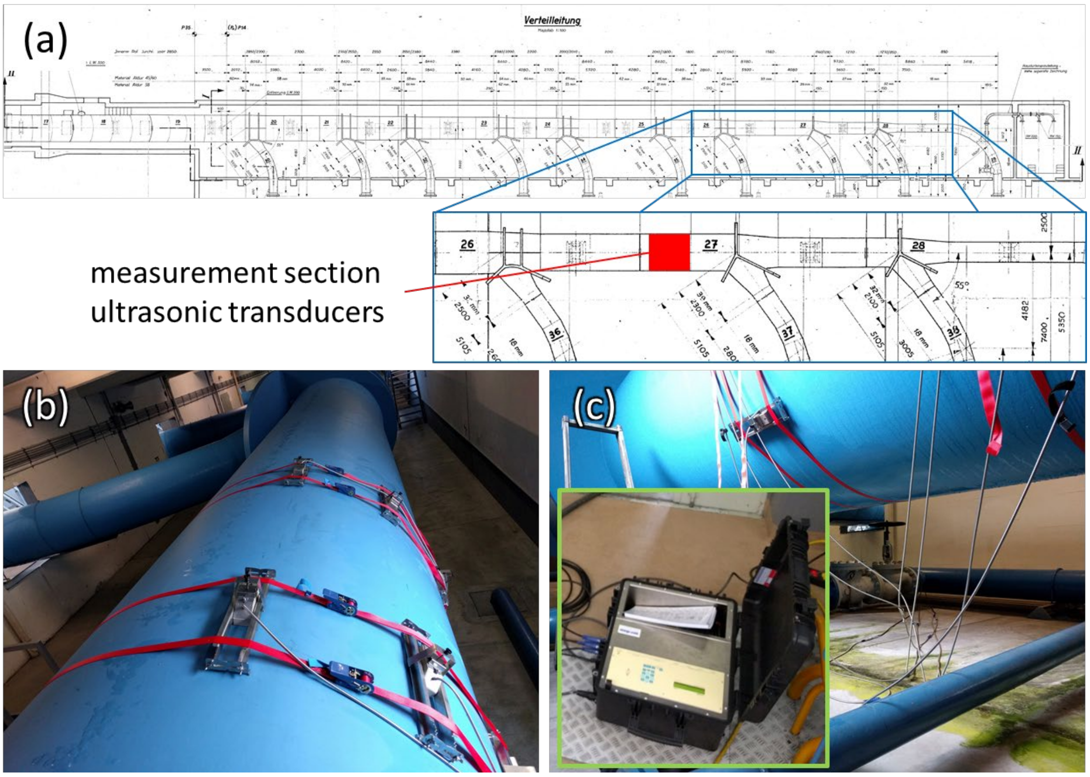

FIGURE 3: CLAMP-ON ULTRASONIC MEASUREMENT

3 Results

Figure 4 shows the comparison of the discharges for the two measurement methods. For this purpose, a flow rate was calculated applying the thermodynamic method with the known generator efficiency. This flow rate was taken as a reference for the further investigation and compared with the flow rate measured with the clamp-on ultrasonic measuring device. Excellent linearity can be seen.

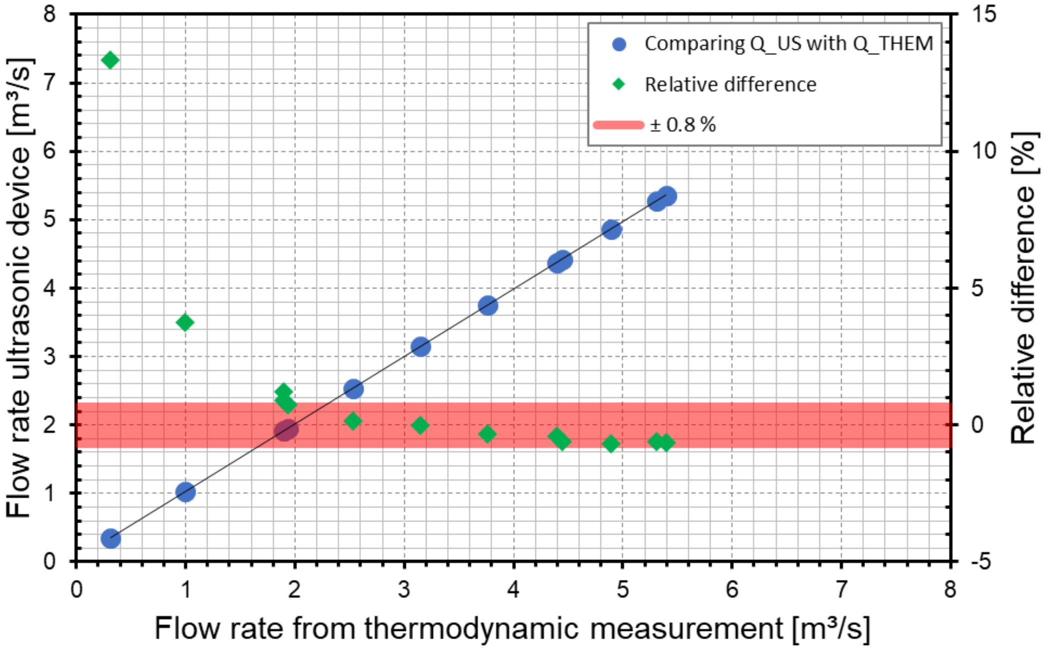

FIGURE 4: COMPARISON OF ACOUSTIC AND THERMODYNAMIC MEASUREMENT – RELATIVE ERROR IN FLOW RATE

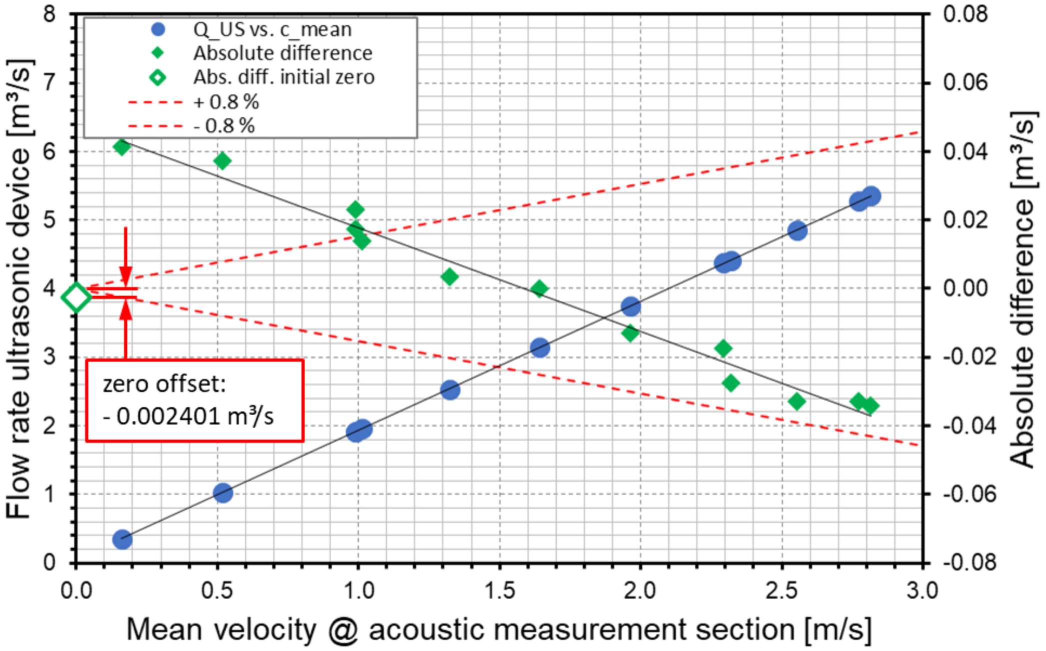

FIGURE 5: FLOW RATE AND ABSOLUTE ERROR FROM ACOUSTIC MEASUREMENTS SYSTEM VS. THE MEAN VELOCITY AT THE ACOUSTIC MEASUREMENT SECTION

Figure 4 shows a straight fit line based on the measuring points. The resulting relative difference calculated from the actual measurement value is also depicted and is ± 0.8% within the relevant operating range.

Figure 5 shows a more detailed analysis of the difference between the ultrasonic and the thermodynamic measurement. The flow rate from the ultrasonic device and the absolute difference between the ultrasonic and the thermodynamic measurement are drawn versus the mean velocity at the acoustic measurement section. From the values for the absolute difference an error in pitch and a zero offset can be observed.

An error in pitch means that the absolute difference values are on a straight line, but the line is not horizontal. The ultrasonic transmitter's pitch is the scaling factor in calculating the flow rate from the measured velocity. Therefore the units are [m^3/s / m/s] or simpler [m^2]. The actual value for the application discussed is 1.91625 m^2.

The zero offset has been checked with all machines out of operation and no flow through the pipe. An initial zero measurement has provided a flow rate value of - 0.002401 m^3/s (see Figure 5). However, there are three main sources for these uncertainties that will be discussed:

First, measuring the pipe's inner cross-section area must be considered. With the power plant in full operation and a filled pressure line, only the outer circumference measurement with a tensionless steel tape measure is possible. The outer diameter was measured to be 1628 mm. To compute the inner diameter, the wall thickness is also necessary. No trusted value could be taken by measuring the wall thickness with an ultrasonic thickness measurement device. Therefore the decision was taken to use the information from the pipework drawings. The wall thickness was given at 33 mm. The result was an inner diameter of 1562 mm. Compared to the diameter of 1560 mm shown in the drawings, only a difference of + 0.26% in the internal cross section area. Every circumference is equal to or higher than the actual value so that a negative error in pitch cannot be caused by the measurement method itself. When measuring the circumference, misalignments of the steel tape measure always form an ellipse; therefore the circumference is greater than or equal to the circumference of the circle. In order to explain the error in the pitch only by incorrectly measuring the inner diameter, the inner diameter would have to be 1574 mm. So the wall thickness has to be 27 mm instead of 33 mm. Before the measurement campaign the pipework was undertaken complete maintenance and check. Therefore it is improbable to have a wall thickness 6 mm under the nominal dimensions, whereas the fact has not been taken into account that a thin layer of paint and corrosion protection is applied on the inner and outer surfaces. In conclusion, the cross-section area cannot lead to such an error in pitch.

Second, for computing the hydraulic efficiency according to the IEC standard, the generators electro-mechanical efficiency (from shaft to wire) can be set to 100% with only a tiny error since all other specific energies are much higher than the difference in specific kinetic energy, especially for high head applications as in the Kaunertal power plant. But the generators efficiency strongly influences the computed flow rate from the thermodynamic hydraulic efficiency measurement. For calculating the flow rate from the thermodynamic measurement, the efficiency of the generator has a direct dependency with the flow rate as follows:

$$Q = \frac{Q_{\eta_{Generator} = 1}}{\eta_{Generator}}$$

The data for the efficiency comes from a measurement after the refurbishment of the generator. Therefore, the uncertainty is small and cannot explain the error in the pitch.

Figure 6 shows the necessary difference in generator efficiency versus the mean velocity in the measurement section of the acoustic flow rate measurement. The difference would have to be -8.68%-points in deep part load (~5 MVA apparent power) to 0.666%-points at 41.5 MVA apparent power. In Figure 6, the apparent power and the absolute error in flow rate between ultrasonic and thermodynamic measurements are also depicted. In addition, the above-mentioned uncertainty of ± 0.8% for the relevant operation range is indicated in the diagram.

Third, the remaining and, therefore, most relevant source of error could then be the too short straight pipe upstream of the acoustic measurement section. Although all turbines had been at total shutdown (ball valves closed), except machine no. 5A, a flow disturbance from the upstream Y-pipe could have caused the error in pitch and the zero offset by influencing the flow profile at the measurement section during the measurement campaign (see Figure 7).

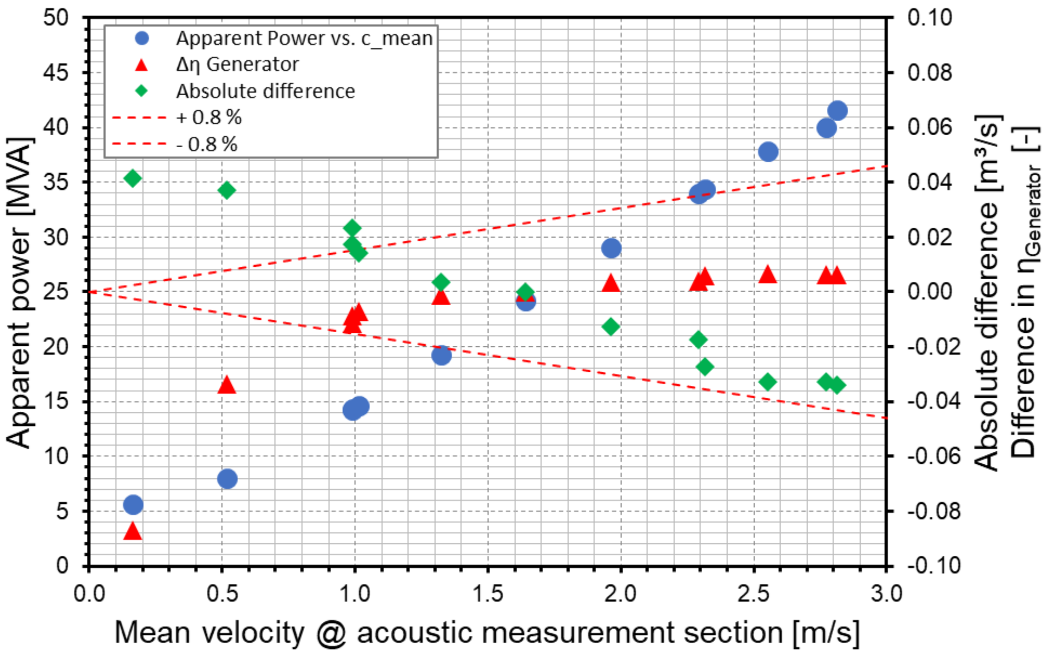

FIGURE 6: ERROR IN EFFICIENCY OF THE GENERATOR AS MAIN SOURCE OF ERROR

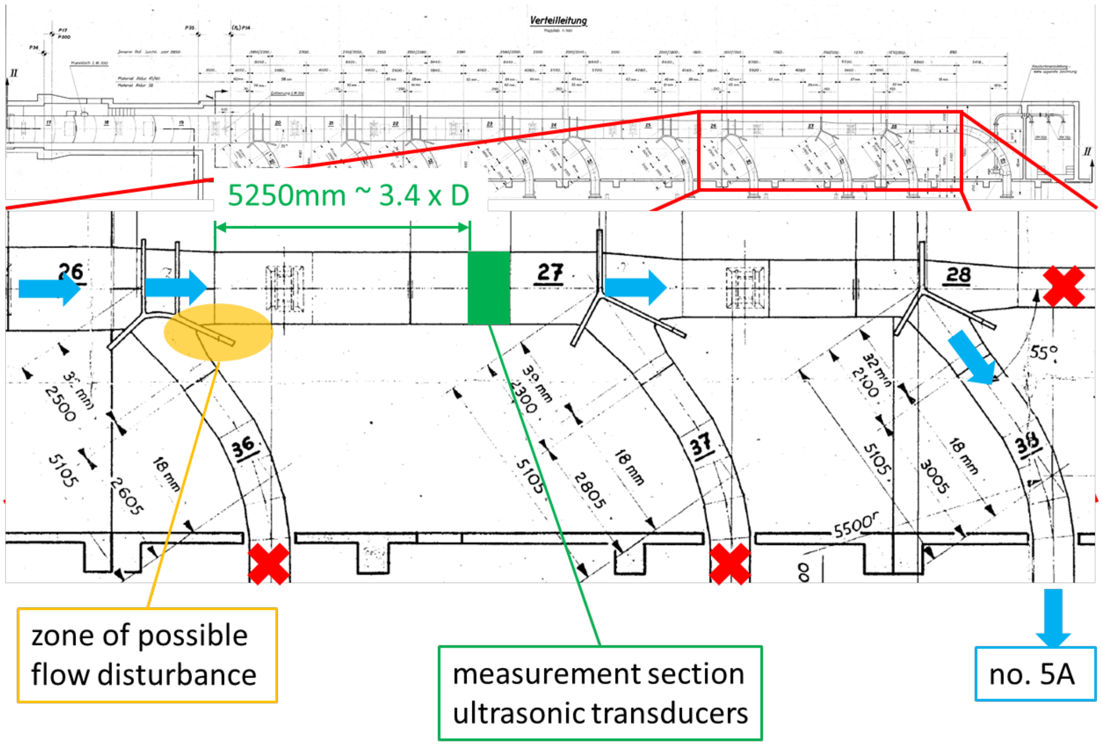

FIGURE 7: DETAIL OF MEASUREMENT SECTION AND POSSIBLE SOURCE OF FLOW DISTURBANCE IN THE FIRST UPSTREAM Y-PIECE

4. Conclusion

The comparison of acoustic transit time flow rate measurement and the flow rate derived from the thermodynamic measurement method shows good results and an absolute maximum difference of ± 0.04 m^3/s in the whole range of operation. The effort for planning and executing the measurement campaign is much less than the thermodynamic efficiency measurement, and the operation range is entirely independent of the head of the hydraulic machine.

As shown above, some sources of error can be eliminated with exact measured values for diameter and wall thickness, but two main problem remain. On the one hand, finding a long and straight section in the distribution pipe to minimize flow disturbance and failures in the symmetry of the flow pattern and on the other hand, any additional outflows between the measuring section and the machine under test must be identified and shut off or included in the measurement.

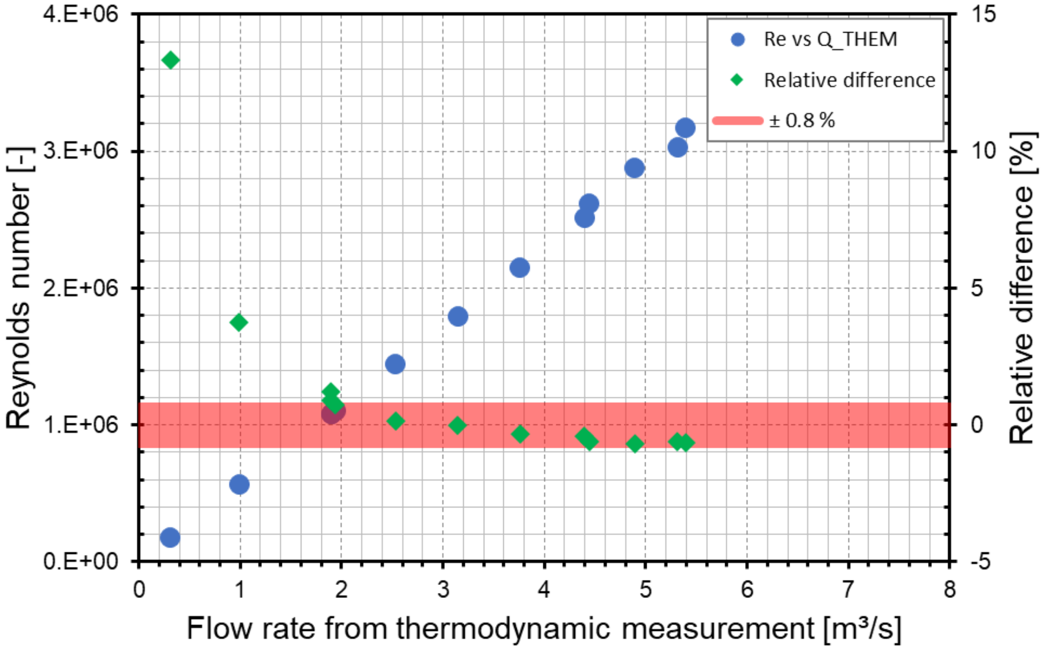

FIGURE 8: RANGE OF REYNOLDS NUMBERS DURIGN THE MEASUREMENT CAMPAIGN

Figure 8 provides an overview of the Reynolds numbers for the whole measurement campaign. According to the manual, the flow pattern must be fully turbulent so that the models stored in the transmitter allow maximum accuracy in calculating the flow rate from the measured velocity. The transmitter's manual states that a Reynolds number above 3000 is required. From practical experience in the field, a minimum of 10000 is recommended to get good results. During the measurement campaign the Reynolds numbers had been between $1.77 \cdot 10^5$ and $3.17 \cdot 10^6$.

5 Bibliography

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