Discharge measurement by means of the pressure-time and the 8-path acoustic method in Niedzica HPP pressure tunnels

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To the memory of Mr Jose Peña, a multiyear erection engineer of Rittmeyer instrumentation and our unforgettable companion during the work in Niedzica Hydropower Plant tunnels

Introduction

Following the recently introduced green certificate system, the renewable energy produced in Polish pumped storage power plants with natural inflow is calculated basing on the amount of water used for generation and that pumped to the upper reservoir. The legislation concerns 3 Polish hydro power plants, including the 92 MW Niedzica HPP at the upper Dunajec river in the southern part of Poland. The plant is equipped with two reversible units with Deriaz pump-turbines of CKD Blansko delivery. Water is supplied to and from the upper reservoir through two pressure tunnels of 7 m diameter. The tunnels are furnished with relief bifurcations, situated close to the spiral case inlets.

In 2005 the Plant applied to the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences (IMP PAN) for assistance in developing a permanent water measurement system. Following the recent experience from an extensive study on such a system for Solina-Myczkowce Complex of Hydro Power Plants, the IMP PAN proposed to furnish the Niedzica pressure tunnels with 8-path RISONIC 2000 acoustic flow meters of Rittmeyer AG delivery. The installation took place in the beginning of 2007 and was followed by commissioning tests headed by an IMP PAN representative.

As the measurement was to be used for energy accounting purposes, it was quite important to make sure that the accuracy declared has been really attained. For this purpose a series of independent discharge measurements using the pressure-time (Gibson) method was carried out in one of the tunnels. Thanks to amendments introduced to the original IEC 60041 procedure and the dedicated instrumentation developed, the IMP PAN team is able now to conduct high accuracy pressure-time measurements both in the turbine and pumping modes of operation. The check measurements carried-out by IMP PAN have demonstrated that the highest discrepancy between acoustic and pressure-time measurement in Niedzica HPP lied still within the uncertainty band of the pressure-time method and it was observed under the most unfavourable measurement conditions (pump operation with measurement close to the spiral case). It can be shown that after introducing a discharge measurement correction of maximum 0.7 %, the discrepancy decreases by over 50 % and the two units show exactly the same performance characteristics.

The acoustic measurement system is used now for various purposes, including determining the performance characteristics and optimisation of cam dependence at both units. Excellent coincidence between performance characteristics based on the model and full-scale tests is observed in the turbine mode of operation whereas some discrepancies have been established in the pumping regime.

1. Background: Polish Green Certificate System and Niedzica Hydropower Plant

Poland is a country with rather poor water resources and moderate technical hydropower potential of 12÷14 TWh/a. Unlike other European countries, only small part of this potential (15 %) has been utilised so far. The large hydropower sector (>10 MW) consists of 12 plants, including 6 pumped storage installations. This situation remains unchanged since 1997 when Niedzica Hydropower Plant was put in operation.

Following the current EU legislation, Poland is expected to rise its renewable energy sector contribution to the electrical energy gross consumption up to 7.5 % in 2010 and 15 % in 2020. Although the national goals are put well below the global EU targets, they are quite a challenge for a country showing hardly 1.5 % index of RES contribution to the electrical energy mix in the beginning of this decade.

In the beginning of 2005 a green certificate system has been introduced in order to promote electrical energy generation out of renewable energy sources. The current system proves highly profitable for various RES sectors, as the average market price of a green certificate (ca. 80 €/MWh) is almost twice higher than that of the so-called black energy (ca. 45 €/MWh) and the Ministry of Economy controls efficiently the market demand.

Unfortunately, due to strong opposition from the green oriented NGOs (non-governmental organisations) and politicians, the recently introduced renewable energy promotion mechanisms prove so far insufficient for starting new large hydro projects in this country. On the other hand side, rising pressure from potential investors may be already observed and one cannot exclude a change in the current situation.

All classic hydropower plants and the pumped storage plants with natural inflow may benefit from the green certificate system. However, in case of pumped storage installations the green energy produced has to be calculated using the formula

$$E_{\mathrm{RES}} = E_{\mathrm{tot}}\,(1- V_{\mathrm{pump}}/V_{\mathrm{turbine}}) \qquad (1)$$

with E_{RES} denoting electrical energy produced from the renewable energy source, E_{tot} – total amount of electrical energy generated in the hydropower plant under consideration, V_{pump} – volume of water pumped to the upper reservoir, V_{turbine} – volume of water used for turbining purposes.

Following the decision of the Minister of Economy [1], all values on the right hand side of formula (1) should be recorded and the records should be kept in an unaltered form for a period of at least 5 years. In practice this regulation implies the requirement of installing a permanent discharge measurement system. According to the interpretation of the Energy Regulatory Office (URE), calculating the volume of water basing on the performance characteristics of hydraulic units was allowed only in the transitional period, till the beginning of 2007.

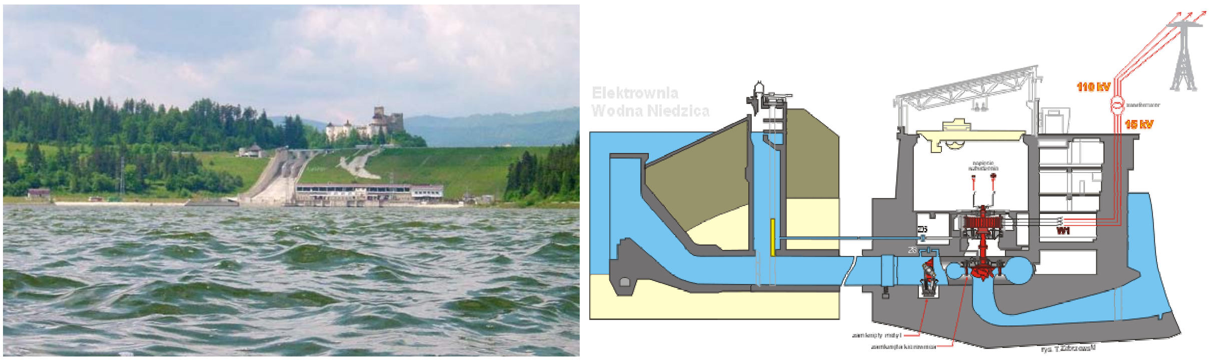

Fig.1 Niedzica Hydropower Plant. A view from the lower reservoir and a simplified cross-section

This decision affects 3 Polish power plants, including the already mentioned Niedzica HPP. The Niedzica HPP is situated at Dunajec river, in the picturesque Podhale valley extending to the north of the Tatra mountain range, at the Polish/Slovakian border. The Niedzica Dam plays today a key role in the regional flood protection and water management system. The plant is equipped with two Deriaz pump-turbines of CKD Blansko delivery (Fig.1, Table 1). Water is supplied to and from the upper reservoir through two concrete pressure tunnels of 7 m diameter. The tunnels are furnished with relief bifurcations, situated close to the spiral case inlets (Fig.2).

Table 1 Main parameters of Niedzica hydraulic units

mode of operation	turbine	pump
installed discharge, m³/s	130	114
installed power	46.375	44.5
head range, m	21 ÷ 49	22 ÷ 46
rated values		
head, m	39.1	40.6
discharge, m³/s	127.9	98.5
active power, MW	43	43.3
rotation speed, rpm	166.7	
runner diameter, mm	4300	

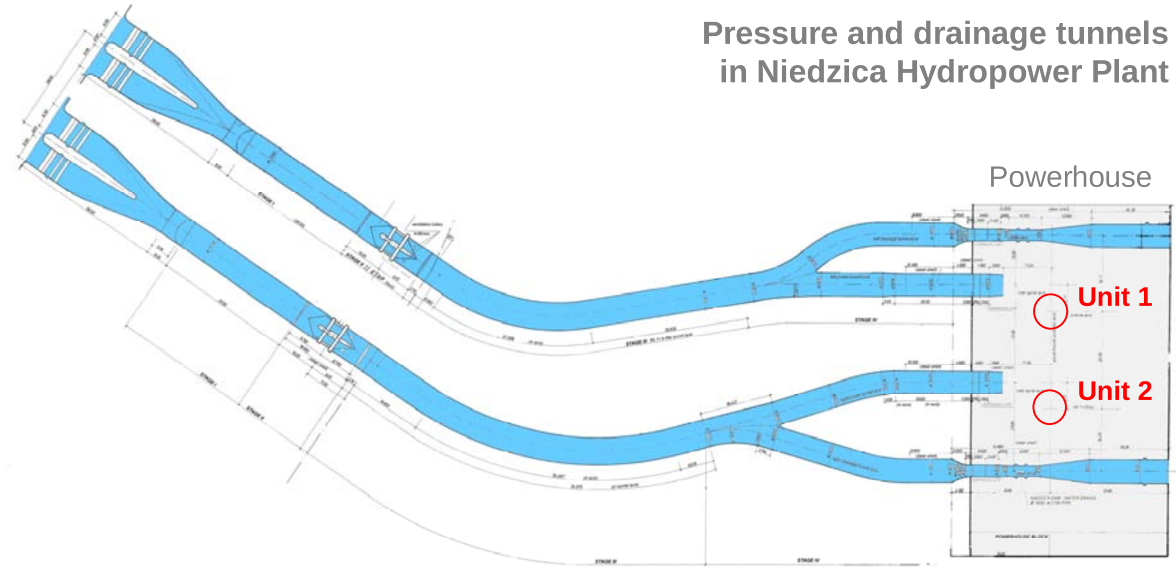

Fig.2 The HPP Niedzica system of pressure and drainage tunnels

In 2005 the Niedzica Complex of Hydropower Plants Co. (ZEW Niedzica SA) applied to the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences (IMP PAN) for assistance in developing a permanent water measurement system. The client assumed the system to be used both for green energy accounting system and for the power plant optimisation purposes (including possible cam curve optimisation in both modes of operation). In view of the above, discharge measurement accuracy comparable with that of typical acceptance tests was required and check tests using an independent method were assumed. Since Winter-Kennedy method is unsuitable for pumping mode of operation, the acoustic method remained the only reasonable option. As there was no access to the tunnel walls from outside, internally mounted ultrasonic transducers had to be used.

The IMP PAN was well prepared for the job as some time ago it conducted check tests of an ultrasonic flowmeter installation in the Zarnowiec Pumped-Storage Power Plant [2]. The pressure-time (Gibson) technique was used as an independent method. Later on, the IMP PAN team applied the same method for numerous discharge measurements in internally accessible pressure tunnels [3]. In 2004 the IMP PAN conducted also a feasibility study on an ultrasonic discharge measurement system for Solina-Myczkowce Complex of Hydropower Plants. After an extensive inquiry among potential suppliers, *Rittmeyer Ltd* was shown as the only company capable to offer suitable equipment at this time [4]. The same recommendation was repeated later on in case of Niedzica project.

2. The acoustic flow measurement method

The acoustic flow measurement methods, based on Doppler effect and transit time principle, have been used for a number of years in various technical applications. However, it was only in late eighties of the last century that the accuracy achieved could have been considered sufficient to incorporate it conditionally into the IEC 41code on acceptance tests of hydraulic turbines, storage pumps and pump-turbines [5]. Since attaining sufficient accuracy requires integration of the velocity field in the hydrometric section, the code allows using solely multi-path two-plane transit time method for the absolute discharge measurement purposes (Fig.3).

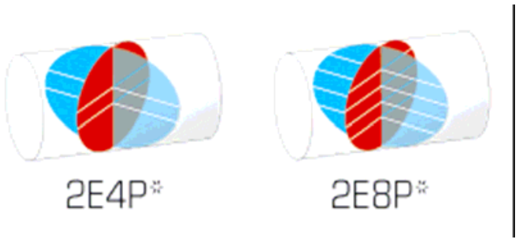

Fig.3 Double-plane acoustic path configurations as applied in filled conduits by Rittmeyer Ltd

The discharge through a circular cross section is determined as an average of discharges calculated for each acoustic plane from the formula

$$Q = k\frac{D^2}{2}\sum_{i=1}^{n} W_i \overline{v_{ai}} \sin\alpha_i \qquad (2)$$

with k correction factor accounting for the error introduced by the integration technique chosen and the conduit shape

D dimension of the conduit parallel to the intersection of the two acoustic planes (Fig.3),

W_i weighting coefficient depending on the number of paths and the integration technique used (e.g. Gauss-Jacobi or Gauss-Legendre quadratures, as recommended by the IEC 41 code),

$\bar{v}_{ai}$ axial velocity averaged along path *i* and calculated from the measured transit times,

n number of acoustic paths in a single plane,

α_i angular location of the path *i* end respective the intersection of the acoustic planes.

There is quite a number of factors that may affect accuracy of acoustic measurement, just to mention:

a) uncertainty in measurement of geometrical parameters and inaccurate positioning of ultrasonic transducers,

b) protrusion effect of ultrasonic transducers,

c) velocity profile distortion due to flow turbulence and some irregularities in the cross section geometry

d) large scale spatial and temporal flow pattern variations

The uncertainty in time measurement due to limited time resolution and delays in triggering the electronic system may be considered negligible with modern instrumentation using high frequency (ca. 1 MHz) signals, if applied to conduits of sufficiently large cross-sectional size and reasonable flow velocities.

The uncertainty in determining the geometrical parameters has been substantially diminished by using computerised theodolite stations with laser instrumentation, which allows for accurate orientation of the theodolite on the targets when determining the hydrometric section geometry and exact positioning of ultrasonic transducers during installation. The scatter in acoustic path lengths can be taken into account by appropriate modification of the IEC 41 recommended W_i coefficients [6]. Additionally, the acoustic path length values can be checked and corrected by measuring the acoustic signal transit time in a flooded penstock during a standstill.

Protrusion effects of ultrasonic transducers may be of some significance in case of smaller diameters. Relevant correction factors can be determined using the CFD techniques. According to Bruttin [7] this correction does not exceed 0.2 % for a penstock of 3 m diameter when an MFUKAN Rittmeyer transducer is applied.

CFD techniques may be also applied to account for the turbulence effect on the mean velocity profile and some irregularities in the hydrometric section geometry. To calculate the integration coefficients with reduced Reynolds number dependent error in case of fully developed, turbulent flow profiles, the *Rittmeyer Ltd* uses often the OWICS (Optimal Weighted Integration for Circular Sections) as developed at the Swiss Federal Institute of Technology in Zurich (ETH Zürich). Extensive studies, conducted at Rittmeyer headquarters and the Swiss Federal Institute of Technology in Lausanne (EPF Lausanne), prove high effectiveness of this technique [6,7].

Large scale spatial and temporal flow pattern variations downstream flow disturbance sources (e.g. pump outlets, valves, gates, diffusors, penstock bends and bifurcations) are a matter of major concern in case of most discharge measurements. Double-plane acoustic path configuration usually compensates for some secondary flow effects and sophisticated computational techniques help to diminish the related bias error in acoustic measurements, but these measures may show limited effect in case of severe flow disturbances [8]. In numerous hydropower applications keeping to the requirements imposed in past decades on location of ultrasonic equipment in respect to the flow disturbance sources is also unrealistic. Therefore, careful selection of hydrometric section is needed in order to keep the measurement uncertainty as low as possible. This was also the case in Niedzica HPP.

3. Installation work and commissioning tests in Niedzica HPP

The original suggestion of the Supplier was to locate measurement sections in the inlet segments of the tunnels (upstream the gate towers). This had to be abandoned since access to the intake structure requires partial dewatering of the upper reservoir (Czorsztyn Lake), which is conducted only once within a decade. Therefore, the Supplier followed the IMP PAN proposal and selected measurement sections located 34 m upstream the unit 1 bifurcation and ca 20 m downstream the unit 2 gate tower axis[1]. Eventually the unit 1 measurement section was shifted by 6.80 m towards the bifurcation in order to increase the distance from the tunnel elbow upstream.

Due to expected velocity field fluctuations resulting from the secondary flows and the hydraulic machine operation, the RISONIC 2000 system with double-plane 8-path (2E8P) configuration was adopted. The system uses MFATB2 ultrasonic transducers (Fig.4) which serve both as ultrasonic signal emitters and receivers and are directly connected to the signal transmission and processing unit. The single velocity measurement is based on a package of 11 transition time samples which is subsequently reduced to 5 by rejecting 6 most outlying values.

[1] All “upstream” and “downstream” terms refer to the turbining flow direction.

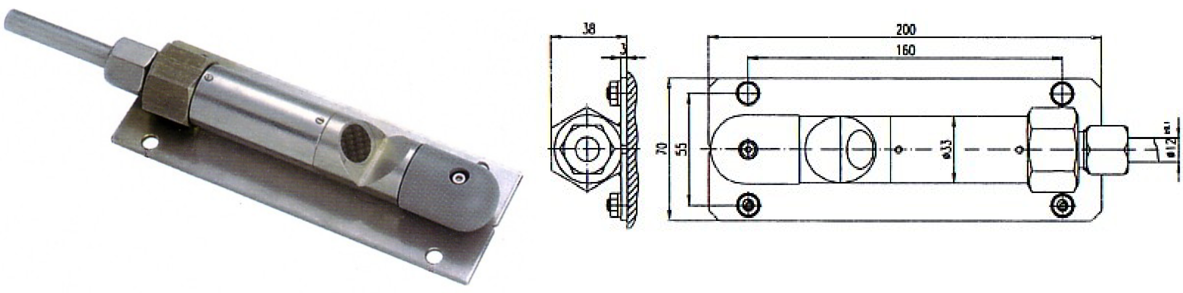

Fig.4 MFATB2 ultrasonic transducers

This is done in order to diminish the uncertainty due to high frequency velocity fluctuations. The effect of low frequency fluctuations is controlled by the relaxation parameter adjusted in the time domain digital filter.

The flowmeters were installed in January (unit 2) and March (unit 1) 2007 by joint effort of the Supplier, Power Plant staff and *Hydronur* installation company. Low inclination angle of the tunnels (7°) favoured swift and effective work of all teams. Applying additional distance bolts and filling the gaps between the wall and transducer plates with durable sealing material solved some problems in final positioning of transducers due to high roughness and inaccurate finishing of the tunnel wall surface. Ventilation tubes were used to conduct the signal conduits to the processing units located in the gate tower control rooms. The Supplier selected the Gauss-Jacobi quadrature algorithm for discharge calculation. Some time after commissioning, the Power Plant staff connected the RISONIC 2000 processing units to the Power Plant control room instrumentation, including the "green energy counter" supplied by Gdansk Division of the Institute of Power Engineering.

Each installation was followed by commissioning tests aimed to prove proper operation of the system and lack of significant errors in measurement results. As no alternative method of discharge measurement was available at this time, use was made of performance characteristics derived by CKD Blansko from the laboratory tests of the pump-turbines.

For this purpose, the submitted turbine mode characteristics in form of $P = P(Q)$ curves as drawn for 4 heads were replaced by $Q_H = Q_H(P_H)$ curves with

$$Q_H = Q/\sqrt{H} \quad \text{and} \quad P_H = P/H^{3/2} \tag{3}$$

denoting specific discharge and power output values, respectively (Fig.5). As the curves drawn for H = 39.1 and 46.1 m heads were almost undistinguishable, there was no problem in determining the relevant values for the actual head of 41 to 42 m. The procedure showed highly satisfactory coincidence between model and ultrasonic measurement results even in case of a 4-path configuration as tested in January 2007 (Fig.6).

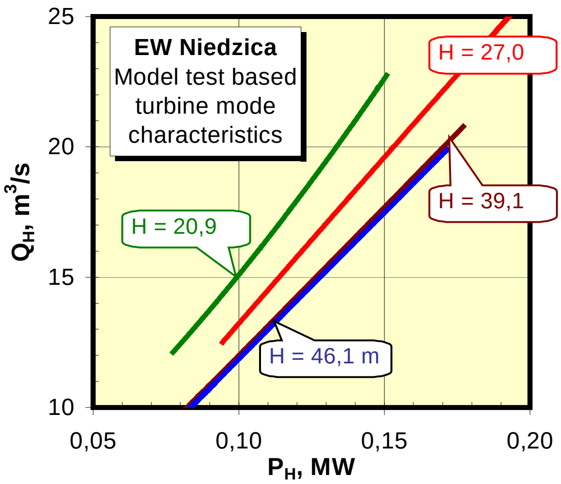

Fig.5 Model test based performance characteristics of Niedzica units in turbine mode of operation

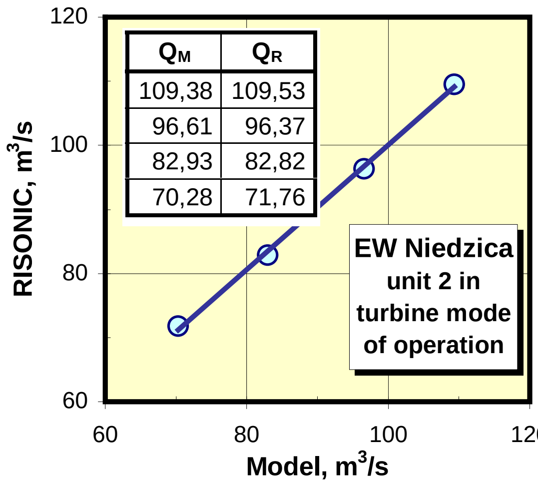

Fig.6 Discharge as determined from the model test results and measured by means of the 4-path ultrasonic system

In case of pump operation use had to be made of efficiency characteristics of the units $\eta = \eta(H)$. This time the discrepancy in discharge measured by means of the RISONIC 2000 system and established basing on the performance characteristics exceeded the 5 % threshold. As such a discrepancy was observed for both machines, there was little fear that the ultrasonic measurement might be in error. However, it was an independent measurement that was expected by ZEW Niedzica to give the final response on this issue.

4. Acceptance tests

The pressure-time (Gibson) method is based on the second law of dynamics applied to the decelerated bulk of liquid flowing through a closed conduit. The inertia force of the liquid stopped in a cylindrical segment of the conduit between reference sections 1-1 and 2-2 follows from equation.

$$p_1 + \rho g z_1 = p_2 + \rho g z_2 + P_f + \frac{\rho L}{A} \cdot \frac{dQ}{dt}, \tag{4}$$

where A and L are the cross-sectional area and length of the measuring segment, respectively, p_1 and p_2 are mean static pressures in the reference sections, z_1 and z_2 – weight centre elevations of these sections, ρ – water density, P_f – pressure drop caused by friction losses (hydraulic resistance).

Integrating equation (4) in the time interval (t_0, t_1), in which the discharge varies from the initial value Q_0 to the final value Q_1, yields the formula:

$$Q_0 = \frac{A}{\rho L} \int_{t_0}^{t_1} [\Delta p(t) + P_f(t)]dt + Q_1, \tag{5}$$

with $\Delta p = p_2 + \rho g z_2 - p_1 - \rho g z_1$. In case of complete stopping the liquid flow through a hydraulic machine, Q_1 is the leakage rate through the cut-off device (typically: wicket gates) and Eq (5) may be used for calculation of the initial discharge. Hydraulic loss value P_f is determined with satisfactory accuracy using its dependence on the discharge square. The leakage depends generally on the pressure difference at the cut-off device. The relevant dependence is usually established from a leakage test at standstill conditions or from the width of gaps in the closed wicket gate apparatus.

The pressure-time method is recommended by the IEC 41 code as one of the primary discharge measurement methods. However, till wide spreading of the computerised data acquisition techniques, its practical application was rather limited in Europe. The situation changed within the last two decades. In mid nineties the method was introduced into IMP PAN practice by one of co-authors of this paper. After introducing some amendments and refinements to the IEC 41 code procedures, the method has been used successfully on numerous occasions also in the pumping mode of operation, e.g. [9]. Nowadays, the method is widely applied in various options and configurations. Utilising specialised experimental and computational techniques enables its employment also in case of non-cylindrical measuring segments, including segments encompassing the intake structure.

Due to its advantages, the pressure-time method was selected for checking the ultrasonic flowmeters in Niedzica Hydropower Plant. As the pressure-time method uncertainty was expected to be higher than that declared by the ultrasonic system supplier, deviation of measurement results exceeding uncertainty bands of both methods was considered a criterion of possible failure in keeping the acoustic system accuracy declarations.

Following decision of the Power Plant owner, direct comparison between ultrasonic and pressure-time method results concerned only unit 1. Therefore, assessment of the unit 2 system was possible only basing on comparison of discharge characteristics following from acoustic measurements in both tunnels.

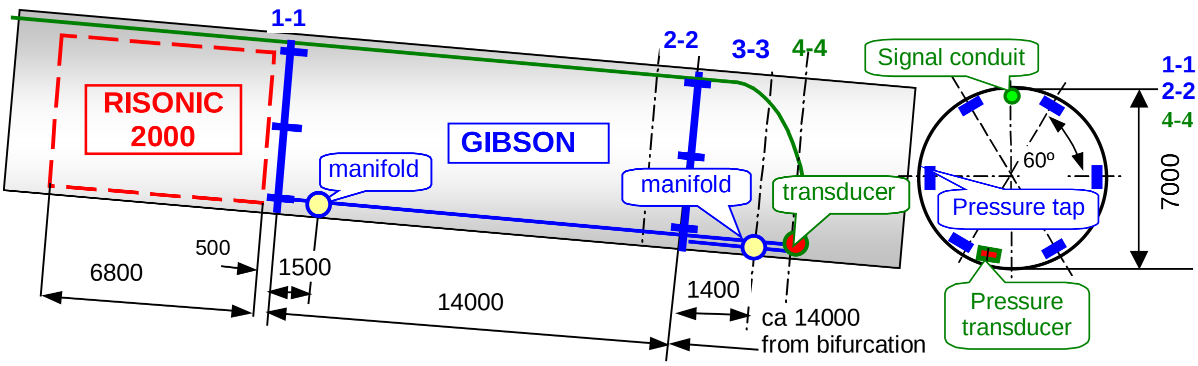

Fig.7 Schematic of the Gibson method discharge measurement system in the unit 1 pressure tunnel

Due to lack of long rectilinear tunnel segments, the pressure-time method measurement segment had to be located immediately downstream that of the ultrasonic method. After shifting the ultrasonic transducers by 6.80 m towards bifurcation, the length of the pressure-time measurement segment had to be shortened to 14 m. The distance to the bifurcation was also ca. 14 m, which implied keeping still to the IEC 41 recommendations. The internal mounting dedicated instrumentation, including pressure tap strips, manifolds and a differential pressure transducer in hermetic casing, was used (Fig.7). The measuring segment geometry and positioning of all pressure taps were determined by the *Rittmeyer* Ltd team using instrumentation used during the acoustic flowmeter installation. Positioning of the transducer and the manifolds enabled proper watering of all connecting tubes up to the lowest pressure tap in each section.

The LPX 9381 transducer of *GE Sensing* (formerly: *Druck*) manufacture was selected for differential pressure measurement purposes due to its high accuracy and superior dynamic properties. The electrical pressure signal was transmitted to the gate tower control room, using electrical conduit introduced into the protective tubing, which was mounted together with that of the ultrasonic transducers. The existing electrical infrastructure was used to transmit the signal to the data acquisition system in the power plant control room. Discharge calculation was performed off-line, using the self-developed *GIB-ADAM* code [10].

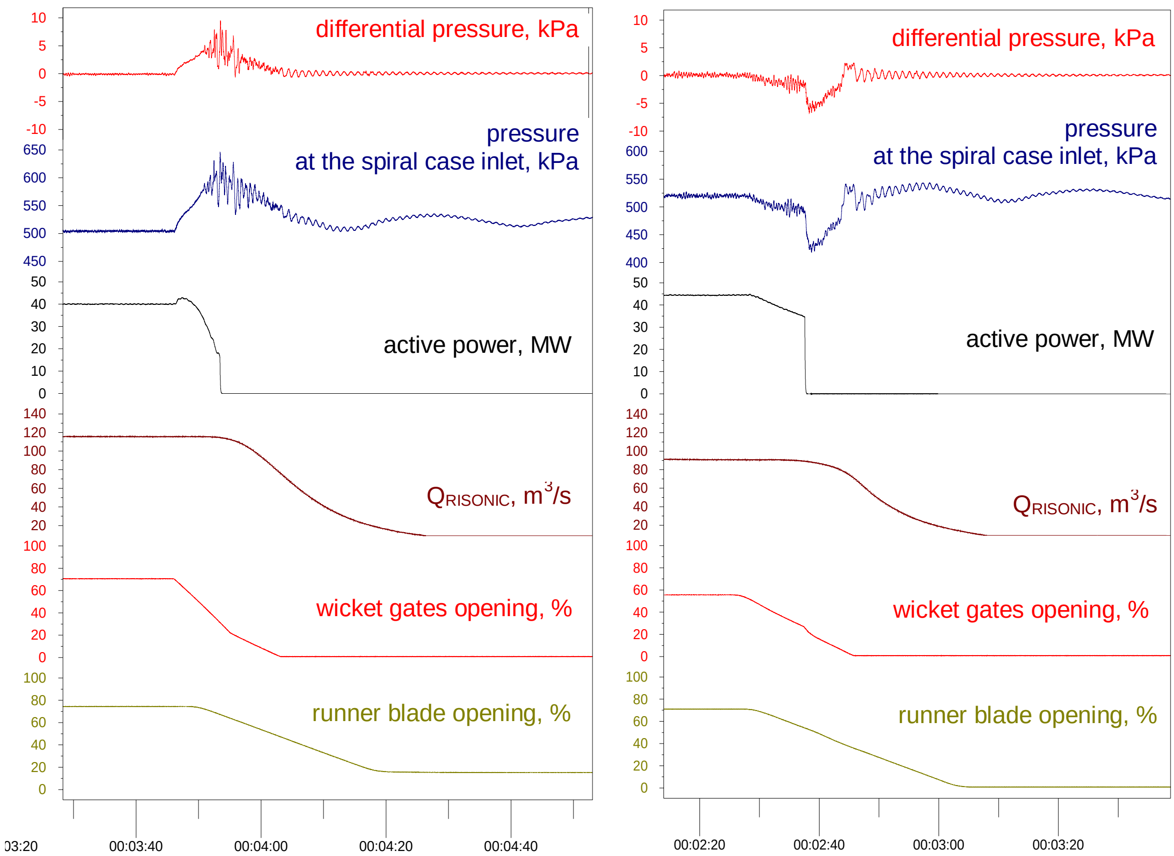

Fig.8 The time course of some performance parameters recorded during discharge measurements by means of the pressure-time method in the turbine (left) and pump (right) modes of operation

Steady-state and Gibson method tests were conducted at 8 loads in the turbine mode of operation with nearly constant head $H = 41 \pm 0{,}4$ m and at 6 operation points in the pumping mode with head varying between 42 and 44.80 m. Typical results in form of time courses of the most significant parameters when closing the wicket gates in turbine mode of operation and complete shutdown in the pumping regime are shown in Fig.8. The steady-state measurements of unit 2 in turbine mode of operation were conducted at $H = 41$ and 44.70 m heads. Comparison of discharge measurement results in the pumping mode of operation had to be based on the optimisation test data.

5. Data analysis and discussion of results

Excellent coincidence between Gibson method and ultrasonic measurement results was stated in case of unit 1 in turbine operation (Fig.9 left). Standard deviation between results for subsequent operation points was below 0,5%. As expected, the ultrasonic measurement coincided also very well with model test based predictions (Fig.9 right). This highly satisfactory result may be surely attributed to favourable measurement conditions with long distance from the intake structure and negligible and/or fully compensated effect of mild upstream elbow.

Due to hydraulic machine induced velocity field fluctuations, secondary flows at the spiral case outlet and possible bifurcation effect, the conditions were much worse in the pumping mode of operation. Nevertheless, the systematic and standard deviation did not exceed the 1.3 % and 1.4 % values, respectively (Fig.10). As deviation stated did not exceed the pressure–time method uncertainty (ca 1.5 %), there was no reason for worry. However, the test executor suggested that the true value may lie between experimental results of the methods used and recommended an 0.7 % upward correction of the ultrasonic measurement for the purpose of high precision measurements [11]. The relevancy of this recommendation has been confirmed by high conformity of performance characteristics of unit 1 and 2 determined basing on the optimisation test results (Fig.11) [12].

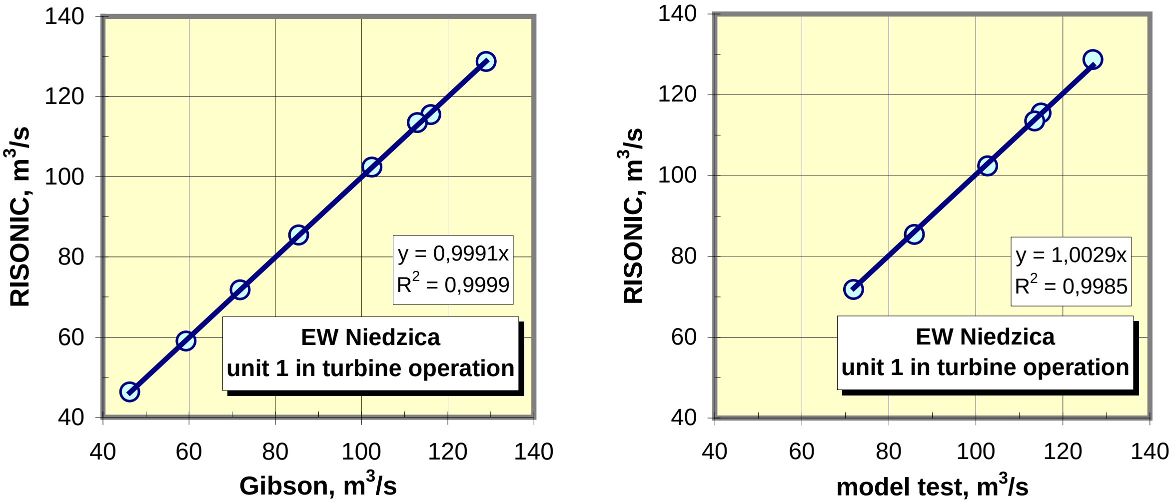

Fig.9 Unit 1 discharge in the turbine mode of operation as measured using the Gibson and ultrasonic methods, and determined basing on the model test results

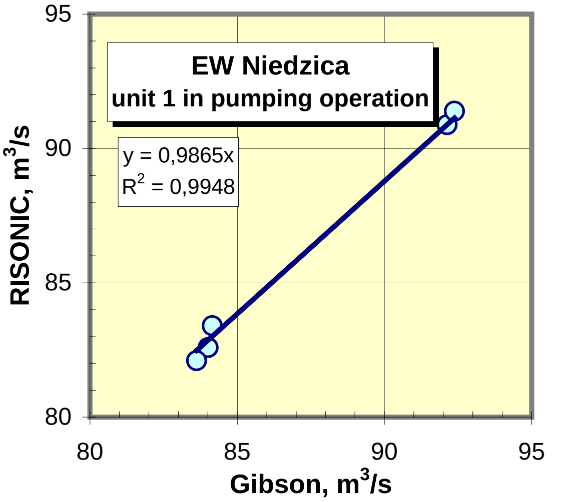

Fig.10 Unit 1 discharge in the pumping mode of operation as measured using the Gibson and ultrasonic methods

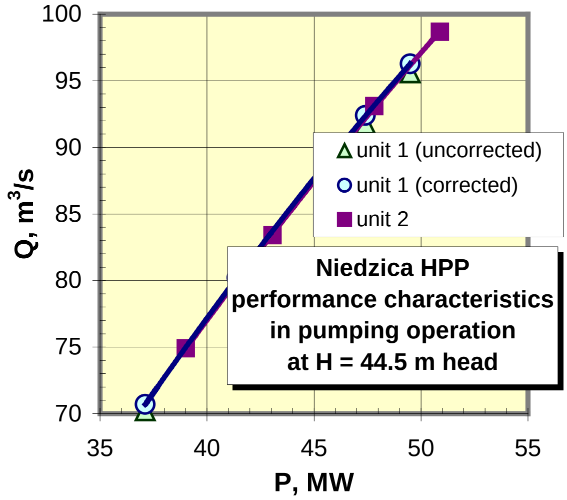

Fig.11 Unit 1 and 2 discharge characteristics as determined using the ultrasonic measurement

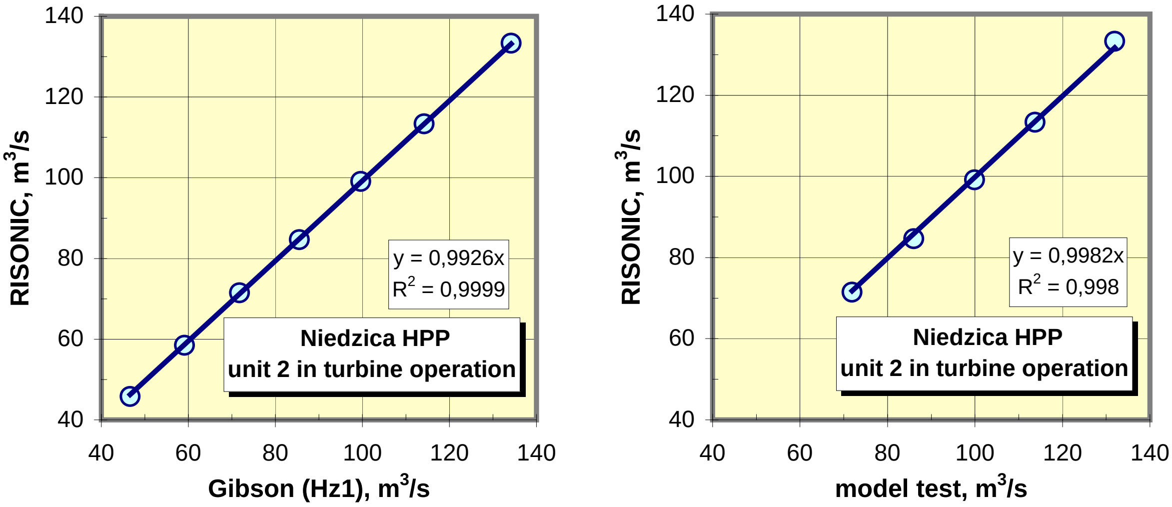

Fig.12 Unit 2 discharge in the turbine mode of operation as determined basing on the unit 1 characteristics following from the Gibson method discharge measurement data, model test results and unit 2 ultrasonic measurement

As already mentioned, the pressure-time method was not applied when testing unit 2 measurement system. The ultrasonic discharge measurement in this case could have been compared solely with relevant data following from unit 1 tests and those resulting from model characteristics. Similar to the results in the 4-path configuration, there was excellent correlation with the model test data. At the same time an 0.7 % systematic deviation with respect to the unit 1 data was stated (Fig.12). While this deviation can be easily explained by various reasons, including measurement uncertainty declared by the Supplier, it is worthwhile to notice that in case of turbine mode of operation measurement conditions in unit 2 tunnel are worse than those in the tunnel of unit 1.

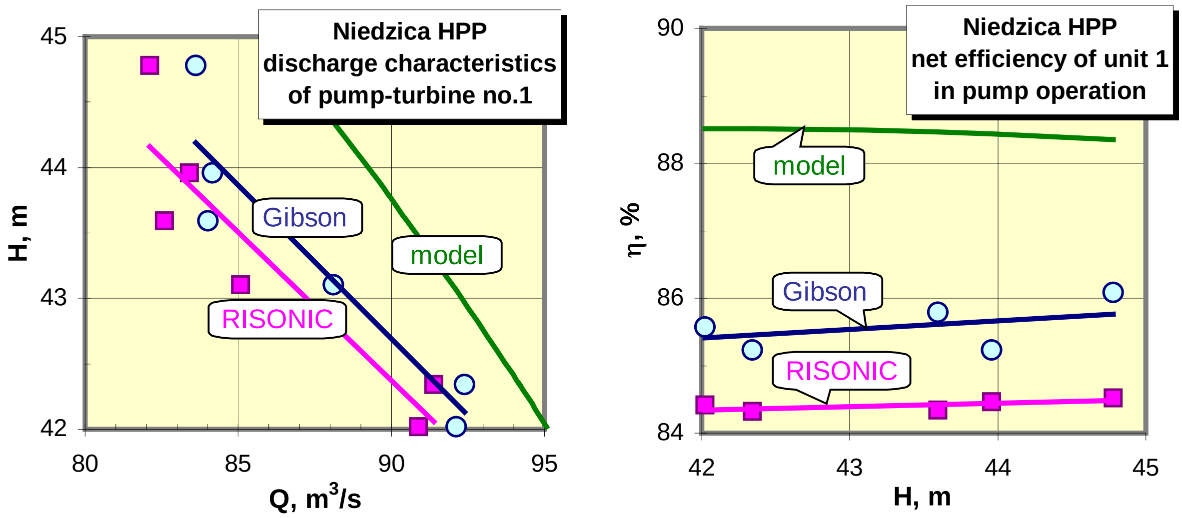

Fig.13 Discharge and net efficiency characteristics of unit 1 in pump operation following from the model test data and established basing on the ultrasonic and Gibson method measurements

Check tests of both machines in pump mode of operation have confirmed substantial discrepancy between performance characteristics as determined basing on model and full-scale tests (Fig.13). The deviation between the RISONIC measurement results and those following from model tests exceeds 6 %. This situation is reflected in the efficiency characteristics, which show efficiency of a full-scale machine by about 3.5 % lower than that expected basing on model tests.

6. Further experience

Following commissioning of ultrasonic measurement systems, the IMP PAN team conducted optimisation tests aimed at determining optimum cam characteristics in both modes of operation, at heads ranging down to 27 m [12]. This was a rare opportunity, as after 10 years since the first filling, planned lowering of the upper water reservoir was taking place.

The tests confirmed high conformity of turbine mode characteristics. However, increased discrepancy between pumping mode characteristics could have been stated at H = 35 m head. The discharge measured in unit 1 tunnel was by 1.5 % lower than that in unit 2 tunnel at the same head and optimised operation point. This was reflected in optimised efficiency curves drawn for H = 35 and 45 m heads. The deviation is still within the uncertainty band of any possible verifying method and can be explained by various reasons, including true difference in machine performance. However, one cannot exclude increased flow velocity fluctuation and/or secondary flows at off-design point of pump turbine operation. This effect must have been more significant in the discharge measurement section situated closer to the spiral case outlet. As the discrepancy is still within uncertainty band of most acknowledged discharge measurement methods and occurs at rarely encountered conditions, there was no pressure on a study aimed at explanation of its true reasons and no further analysis, including that of the velocity records in individual acoustic paths, was taken on.

7. Conclusion

1. The ultrasonic discharge measurement instrumentation installed in Niedzica Hydropower Plant is in faultless operation for over 1.5 year, contributing essentially to the local green energy accounting system.
2. The ultrasonic discharge measurement systems confirmed the model test based characteristics of hydraulic units in the turbine mode of operation and showed that the pump mode characteristics are less advantageous than those submitted by the hydraulic unit supplier.

3. The analysis of the check and optimisation test results proves that the accuracy of the installation fulfils the expectations in both modes of operation and can be hardly challenged by any other discharge measurement method. The accuracy is especially high in the turbining mode of operation.

   As Winter-Kennedy method cannot by applied under pumping mode of operation there is in fact no reasonable alternative option for permanent discharge measurement system of reversible hydraulic units.

4. In the pumping mode of operation the velocity field fluctuations probably affected to some extent both the ultrasonic and the check (pressure-time) method measurement as applied close to the spiral case outlet. This effect might have been higher at off-design points of operation. While the deviations observed do not raise any practical concern for the user, they show also that the precise discharge measurement at a large pump outlet remains still a major challenge for the measuring instrumentation suppliers.

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