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WATER TURBINE EFFICIENCY MEASUREMENTS USING THE GIBSON METHOD BASED ON SPECIAL INSTRUMENTATION INSTALLED INSIDE PIPELINES

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Summary:

Water discharge measurement is the essential and very difficult task of hydraulic machinery performance tests under field conditions. It is especially complex in water power plants with no access to the flow system from outside, and no suitable measurement installations prepared during construction. Among few available water discharge measurement methods, the pressure-time (Gibson) method is very attractive nowadays. The late worldwide growth of interest in this method results from replacing the traditional recording techniques by digital (computer-based) data acquisition systems to obtain the pressure-time curve. Therefore, the method is now more competitive than before. Preparation to use this method is relatively simple in a penstock with an access from outside. However, the difficulty grows in configurations with no access requiring sophisticate installation of pressure measurement systems inside the penstock.

This paper presents special measurement instrumentation installed inside a penstock in order to enable measurement of pressure variations, for application of the pressure-time method in order to determining the flow rate. The instrumentation has been developed in the Szewalski Institute of Fluid-Flow Machinery of the Polish Academy of Sciences in Gdansk (Poland) for use in the pressure-time method, which in turn has been used on several large power water turbines in Poland and in Mexico. The examples of the applying the prepared instrumentation in efficiency tests of a certain turbine are presented together with selected test results. The results of calibrating the Winter-Kennedy measuring system for monitoring of flow rate through this turbine are also presented.

1. INTRODUCTION

One of the most difficult tasks to be achieved in order to investigate water turbine efficiency in hydropower stations is the measurement of water discharge. Special difficulties emerge in old dam power plants, in which no suitable measuring instrumentation has been installed during construction, and the access to the turbine flow system from outside is not possible.

In recent years, a method frequently used for measuring water discharge in hydropower plants is the pressure-time method [11, 14, 15, 16]. This method, also known as the Gibson method, is one of the few methods suitable for absolute water flow rate measurements. Its use requires installing appropriate instrumentation for pressure measurement at selected sections of the turbine penstock. This task is extremely difficult and expensive when this penstock is not exposed to external access.

The article presents special instrumentation that makes it possible to measure the water flow rate that go through water turbines based on the Gibson method for cases when there is no external access to the flow systems of those turbines. The measuring instrumentation was manufactured in the Robert Szewalski Institute of Fluid-Flow Machinery, Polish Academy of Sciences, Gdansk (IF-FM-PAS) and used in a number of large-power water turbines in Poland and Mexico[1].

2. FLOW MEASUREMENT PRINCIPLE IN THE GIBSON METHOD

The Gibson method utilises the effect of water hammer phenomenon in a closed pipe [11,12,14,15,16]. The method consists in measuring a static pressure difference, which occurs between two cross-sections of the closed pipe as a result of change of momentum. This condition is induced when the water flow in the pipe is stopped suddenly using a cut-off device, a cut-off valve or a turbine wicket gate (guide apparatus). The flow rate is determined by integrating, within a proper time interval, the measured pressure difference change caused by the water hammer effect.

In order to derive a relationship for computing the volumetric flow rate Q we must consider a closed pipe with the flow section area A that may change along its length. Scheme of turbine penstock is shown in Fig. 1, for instance. Next we must consider that the water flow must be stopped. Taking into account one segment of length L, limited between sections 1-1 and 2-2 we assume that the velocity and pressure distributions in those sections are constant. Also it is assumed and that the fluid density and the flow section area do not change with water hammer effect[2].

Following these assumptions, the relation between the parameters of the one-dimension unsteady flow between two selected sections of the pipe can be described using the well-known energy balance equation[3] [10]:

$$\alpha_1 \frac{\rho Q^2}{2A_1^2} + p_1 + \rho g z_1 = \alpha_2 \frac{\rho Q^2}{2A_2^2} + p_2 + \rho g z_2 + \Delta P_f + \rho \int_0^L \frac{dx}{A(x)} \cdot \frac{dQ}{dt} \tag{1}$$

Where ρ is water density, p_1 and p_2 are static pressures in sections 1-1 and 2-2 of the pipe, respectively (see Fig. 1), z_1 and z_2 are hydrometric levels of sections 1-1 and 2-2, α_1, α_2 are the Coriolis coefficient[4] (kinetic energy correction coefficient) for sections 1-1 and 2-2, respectively, and finally, ΔP_f is the pressure drop caused by friction losses between sections 1-1 and 2-2.

The fourth term on the right-hand side of the above equation represents the hydraulic friction losses in the pipe segment. In the Gibson method, the pressure drop caused by friction is determined from a square flow rate function, written as :

$$\Delta P_f(t) = K_f Q(t)\left|Q(t)\right|, \text{ where } K_f = const. \tag{2}$$

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[1] In Mexico, this instrumentation was implemented by the University of State Morelos, Cuernavaca, with the assistance of the specialists of the Robert Szewalski Institute of Fluid-Flow Machinery, PAS, Gdansk.

[2] When using this method one should be aware about differences between the real flow in pipelines and its theoretical model taking into account certain simplifications. Besides the inaccuracy of the applied measuring instruments and that of the numerical calculations, those simplifications are the possible source of inaccuracy of the measuring method. Therefore it is very important for the effects of the above simplifications to be limited and not to generate significant errors when determining the flow rate. In the light of the assumed simplifications we should conclude that they limit the use of the method under discussion to the cases in which the change of fluid density and the deformation of pipe walls due to pressure surge caused by the water hammer are negligibly small. Relative change in liquid density and cross-section area depending on pressure rise Δp can be estimated using the following formulas:

$$\frac{\Delta\rho}{\rho} = \frac{1}{E_c}\Delta p \qquad \frac{\Delta A}{A} = \frac{D}{eE}\Delta p$$

It is worth to say that in overwhelming majority of practical applications of the method in water turbine penstocks relative changes of those quantities are extremely small. For the water turbine systems examined by the authors of the present paper, it did not exceed 0.05 %.

[3] Equation (1) is frequently referred to as Bernoulli' equation for unsteady flow of incompressible liquid.

[4] The value of the Coriolis coefficient for fully developed turbulent flow in the pipeline is within the limits from 1.04 to 1.11.

The last term in equation (1) is the unsteady term, which takes into account the time-history of change of the volumetric flow rate $Q=VA$, recorded during the time period of the water hammer effect. This term [5] represents the effect of fluid inertia in the examined conduit segment.

In order to clarify these considerations some quantities are presented to group terms of equation (1):

- static pressure difference between measuring sections 2-2 and 1-1 related to a reference level:

$$\Delta p = p_2 + \rho g z_2 - p_1 - \rho g z_1 , \tag{3}$$

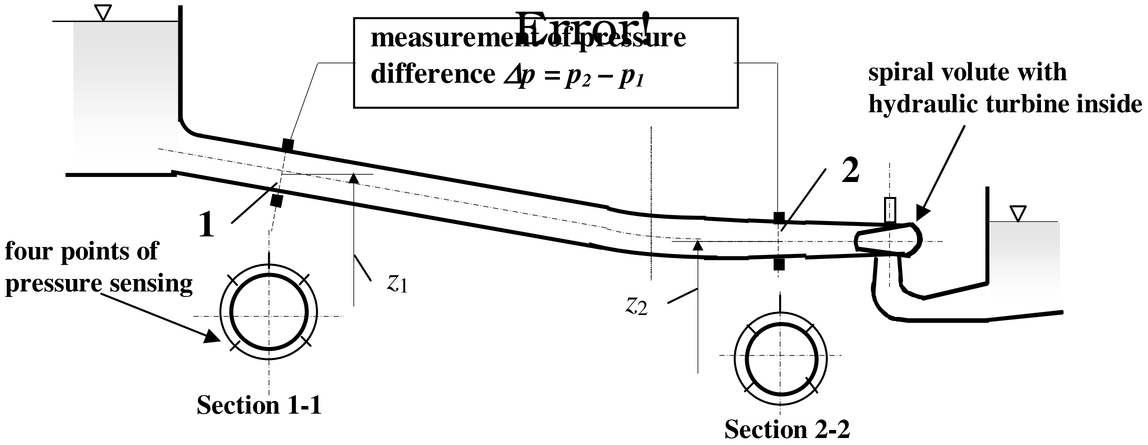

Fig. 1. Scheme of turbine penstock with marked measuring sections used in the Gibson method.

- dynamic pressure difference between conduit sections 2-2 and 1-1:

$$\Delta p_d = \alpha_2 \frac{\rho Q^2}{2A_2^2} - \alpha_1 \frac{\rho Q^2}{2A_1^2} , \tag{4}$$

- geometrical modulus of the penstock segment of a length L:

$$C = \int_0^L \frac{dx}{A(x)} . \tag{5}$$

Then we arrive at the differential equation in the form :

$$\rho C \frac{dQ}{dt} = -\Delta p - \Delta p_d - \Delta P_f . \tag{6}$$

After integrating this equation for the time interval (t_0, t_k), in which the flow changes from initial to final conditions, we obtain the flow rate difference between those conditions. Then we assume that we know the flow rate at final condition (Q_k), i.e. after the cut-off device has been closed, allowing the following expression to be applied for the computation of the volumetric flow rate at initial condition (before starting the water flow cut-off):

$$Q_0 = \frac{1}{\rho C} \int_{t_0}^{t_k} \left(\Delta p(t) + \Delta p_d(t) + \Delta P_f(t) \right) dt + Q_k . \tag{7}$$

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[5] For steady flows this term is equal to zero and then equation (1) takes the form of the Bernoulli equation for the flow of real liquid.

The water flow rate at final condition, if different from zero due for instance to water leaks through the closing device, is to be measured or estimated using a separate method.

Equation (7) shows that in order to determine the water flow rate, it is necessary to determine static pressure difference Δp, the pressure drop ΔP_f caused by hydraulic losses in the pipe segment and the dynamic pressure difference Δp_d between the hydrometric sections 1-1 and 2-2. The latter two values are calculated using their relation to the square of the flow rate, as stated in equation2 (2) and (4).

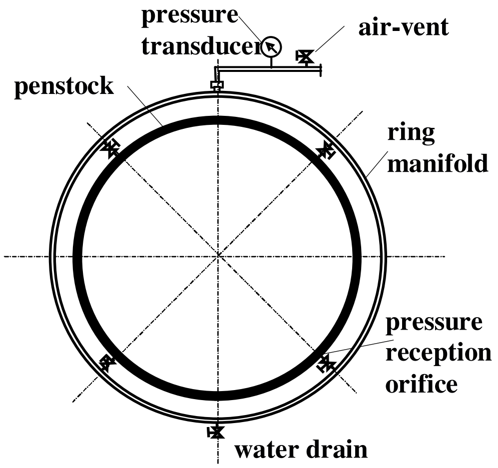
In practice, some variations of the Gibson method are used [1,3,16]. The most important of them include:

1. Direct measurement of pressure difference between two hydrometric sections of the pipe using a pressure differential transducer.
2. Separate measurements of pressure changes in two hydrometric sections of the penstock.
3. Measurement of pressure changes in one hydrometric section of the penstock and relating these changes to constant pressure in the open liquid tank, to which the water system is directly connected.

In the last century, the Gibson method was more frequently used in North America compared with Europe and other parts of the world. The increased accuracy of the devices used for pressure measurements and the use of computer techniques for collecting recorded data and their numerical processing make this method more attractive than dated versions which employed optical techniques to record pressure changes combined with manual graphics.

3. PREPARING SPECIAL MEASURING INSTALLATION

The installation of instrumentation for pressure measurement in selected cross-sections of the penstock is relatively easy when there is access to its external wall. Each of the selected measuring sections requires four pressure sensing points connected to a manifold (see Fig. 2 and Fig. 3).



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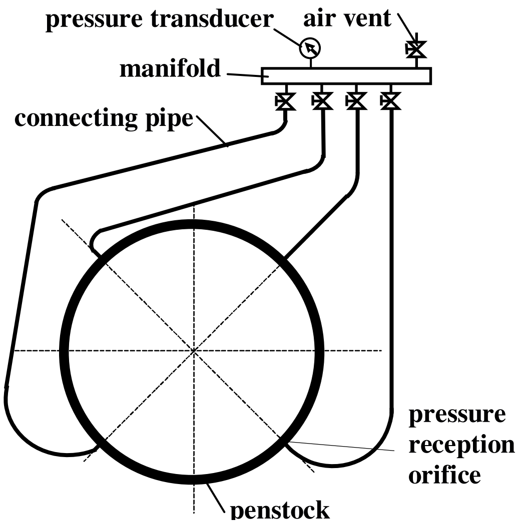

Fig. 2. Scheme of pressure taps (reception orifices) connected to the ring manifold. (case of external access to the hydrometric section of a penstock).

Fig. 3. Four pressure taps (reception orifices) connected through separate pipes to manifold (case of external access to the hydrometric section of a penstock).

Dealing with a large-dimension penstock, without access its outer wall requires all instrumentation as well as installation be prepared from the outside, which represents a challenge. The main concern is that any malfunction, hermetic seal or connection requires emptying the penstock again before any repair can be done. A special measuring system shown below in Figures 4 to 9, was developed in IF-FM PAS for this task. It has been already used in a number of large hydro power stations in Poland and Mexico [4, 5, 6, 7, 8, 9].

A very important component of the special instrumentation is a properly shaped flat bar with a hole for static pressure collection, which is shown in Fig. 4. In order to minimize the perturbation caused by the bar on the streamlines in the vicinity of the hole, it is important that the mounted flat bar: (1) be well designed and constructed with appropriate shaped ends, (2) be smoothly and strongly attached to the pipe wall through welding, and (3) be well machined, taking care of the hole location and geometry. The point is that in the hole area, i.e. where the static pressure is measured, hence, any fluid flow instabilities should be avoided preventing boundary layer separation and recirculation or vortex regions. The thickness of the flat bar is determined by the diameter of the hole and the diameter of the connecting pipe. Its length and profile are designed according to promote stabilisation of the streamlines in the vicinity of the hole. The international standard IEC 41- 1991 may be used as a guide to determine the dimensions of both the flat plate and the drilled hole [16]. According to this standard, the surface of the flat bar should be completely flat and parallel to the streamlines in the area extending to 0.3 m in front of and 0.1 m behind the hole, the least, according to the flow direction. The flat bar and hole are connected through pipes to the manifold, where a pressure transducer is located as shown in Fig. 5. Absolute pressure transducers are used given that waterproof conditions prevail. The standard for application of Gibson method establishes that pressure must be measured with at least class 0.2% accuracy devices IEC 41 [16]. The required high accuracy of the measurement may also be enhanced if the transducer is designed and calibrated as close as possible to the range of the pressure difference defined in practical given conditions. Fast signal processing is used since the water hammer effect last a few seconds only. The transmitted frequency band of the transducer is determined by the frequency of the pressure wave propagated in the examined flow system. The upper limit of this band should be at least 10 times higher then the frequency of the pressure wave generated by the water hammer in the pipeline. Some advantage can be obtained also if the transducer is equipped with a temperature compensation system.

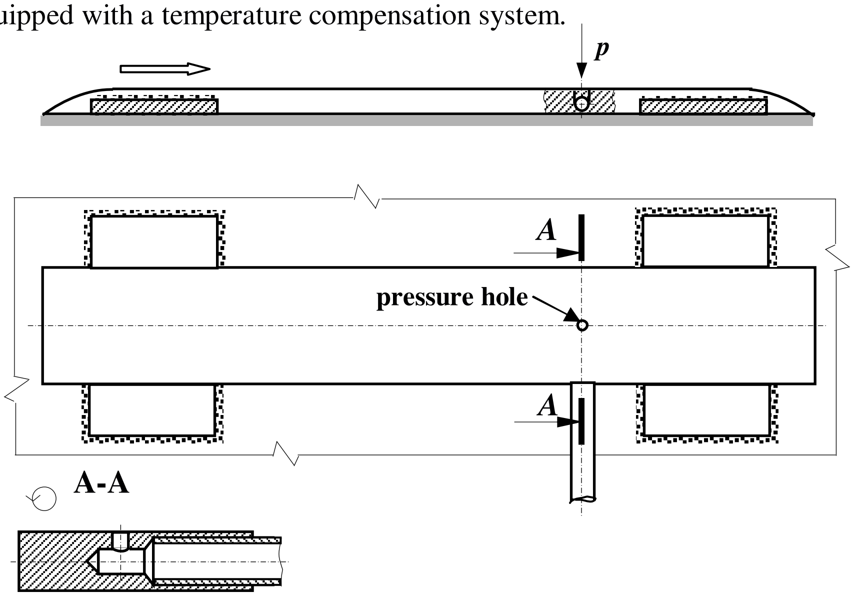

Fig. 4. Flat bar construction characteristics with one hole for static pressure reception orifice.

Once the instrumentation has been mounted it is very important to purge the line. Then, a water filling process follows allowing full deaeration. This process is easy and typical in external installations (Fig. 3, 4), but a special procedure must be followed for cases as the present one[6].

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[6] description of which goes beyond the scope of this article .

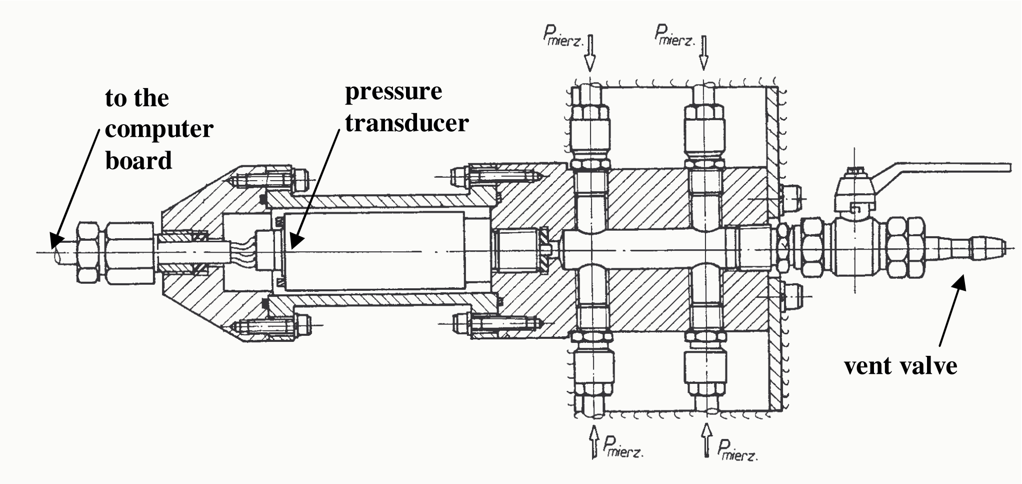

Fig. 5. A waterproof manifold with details of location of the absolute pressure transducer.

4. CHOOSEN RESULTS OF TURBINE EFFICIENCY MEASUREMENTS USING THE GIBSON METHOD

The described method was used for efficiency test of one Francis type high-power (180 MW) water turbine as discussed below. In this case the Gibson method was based on separate measurements of pressure changes in two measuring sections of the penstock. The flow system of the tested turbine is schematically shown in Fig. 6. Four pressure reception orifices, connected to the manifold via copper-made connecting pipes, were installed in each section as shown in Figs. 7, 8 and 9. The pressure in the prepared measuring sections was measured using high-precision class (0.1) semi-conductor pressure transducers equipped with the temperature compensation systems.

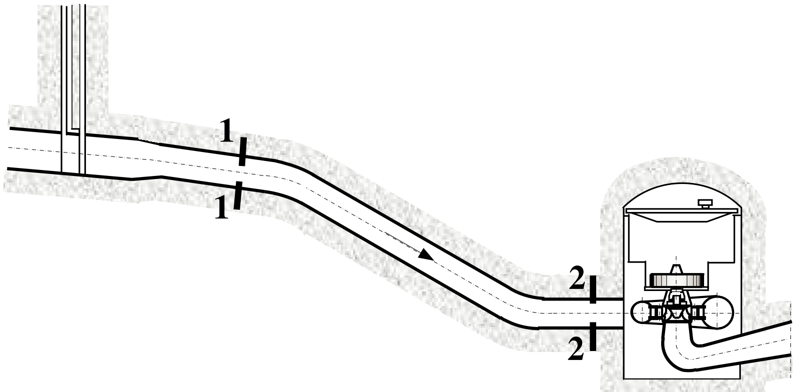

Fig. 6. A schematic of turbine flow system with marked hydrometric sections.

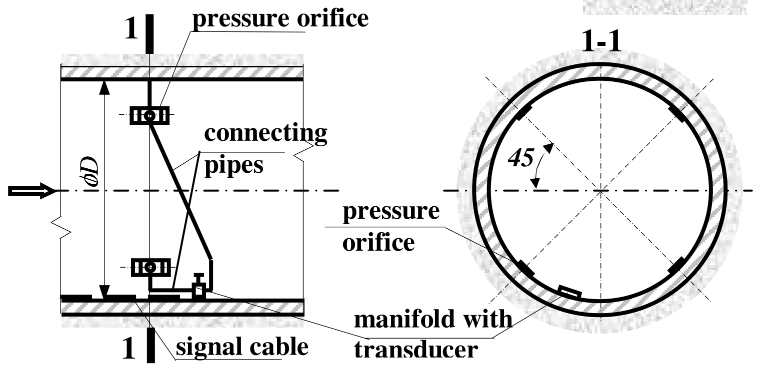

Fig. 7. Distribution of static pressure reception orifices in penstock section 1-1 and their connection to hermetic manifold with absolute pressure transducer installed inside.

The geometry of the measuring segment of the pipeline between sections 1-1 and 2-2 was determined from direct measurements. The inner diameters were measured in more than ten cross sections along the segment, with the accuracy better than 0.2 %. The length of each sub-segment was measured with the same accuracy. Table 1 contains dimensions and details for each sub-segment. The results of those measurements make it possible to estimate the value of the modulus *C* (equation 5) for the entire measuring segment of the penstock.

Table 1. Specification of dimensions and details of penstock sub–segment (between sections 1-1and 2-2)

Element of the penstock	Length	Internal diameter	Internal cross-section area	Modulus C (Eq.5)
-	L [m]	D [m]	A [m^2]	$C=L/A$
Cylindrical segment no.1	6.45	6.5	33.183	0.19437576
Elbow no. 1 (Rm= 23894)	20.2	6.5	33.183	0.60874269
Cylindrical segment no.2	68.94	6.5	33.183	2.07756045
Elbow no. 2 (R= 25800)	20.0	6.5	33.183	0.60271553
Cylindrical segment no.3	19.44	6.5	33.183	0.5858395
Cone	5.4	6.5/5.7	33183/25.518	0.18557294
Cylindrical segment no.3	2.25	5.7	25.518	0.08817428
Total	142.68	-	-	4.34298115

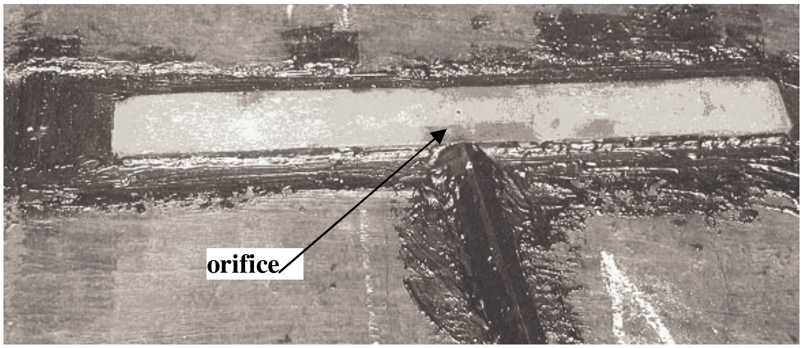

Fig. 8. View of a flat plate with pressure reception orifice used in measuring section 1-1.

Fig. 9. View of the manifold installed in measuring section 1-1, with the absolute pressure transducer mounted inside.

In this case the flow rate at final condition, required by the method, corresponding to the leakage water flow through the closed wicket gate was determined by measuring the water level decrease in the cylindrical penstock segment with constant slope. For this purpose the pressure in the turbine spiral case (a few meters before the wicket gate location) was obtained from its relationship with the pressure resulting from the action of the lower water column (behind the wicket gate) as shown in Fig. 10. At this time the water gates at the penstock inlet were kept tight closed. All water inlets to the penstock were closed as well. The water gates at the exit of the turbine draft tube were disassembled, which provided opportunity for free outflow of the leakage water through the guide apparatus.

The leakage flow rate, determined from the measurements at a low water column, was re-calculated to the conditions when the flow is cut-off during the measurement of the pressure difference produced by the water hammer effect. For this purpose the following relation was used:

$$Q_k = K_{leak}\left(p_t - p_m\right)^{0.5}; \qquad K_{leak} = \frac{Q_{k-m}}{\left(p_{t-m} - p_{m-m}\right)^{0.5}}, \tag{9}$$

in which Q_k is the rate of leakage flow through the guide apparatus after the flow has been cut-off, $(p_t - p_m)$ is the static pressure difference between the two sides of a guide apparatus blade, corresponding to the above conditions, K_{leak} is a constant coefficient determined from the measurements, Q_{k-m} is the leakage flow rate measured for the pressure difference between guide vanes sides equal to $(p_{t-m} - p_{m-m})$.

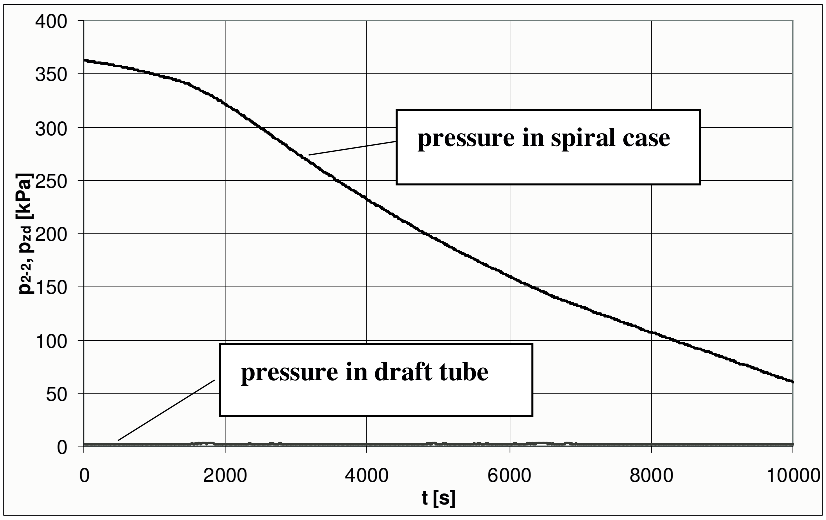

Fig. 10. Pressure changes on the two sides of the turbine guide apparatus, recorded during leakage test.

Each flow rate measurement performed using the Gibson method requires uniform and relatively fast stoppage of the water flow through the turbine using its guide apparatus, with the generator connected to the electric grid. Before each water flow rate measurement, the assumed conditions of hydro-unit's operation were properly adjusted. The quantities were measured using a computer data acquisition system, making use of LabView program and a 16-bit computing board. The data were recorded with a sampling frequency equal to 500 Hz, using low-pass filters with frequency limit to 200 Hz. The input data for water flow rate calculations were prepared in ASCII format with recording frequency of 100 Hz.

The flow rate was determined from the recorded pressure time-histories using a *GIB-ADAM* program developed in the IF-FM PAS. Figure 12 shows a sample of record of the time-history of turbine guide vane closure and the measured pressure difference between the penstock measuring sections, as well as the flow rate time-history determined using the *GIB-ADAM* program. The systematic uncertainty of the flow rate measurement performed using the method under discussion was assessed as approximately equal to 1 %.

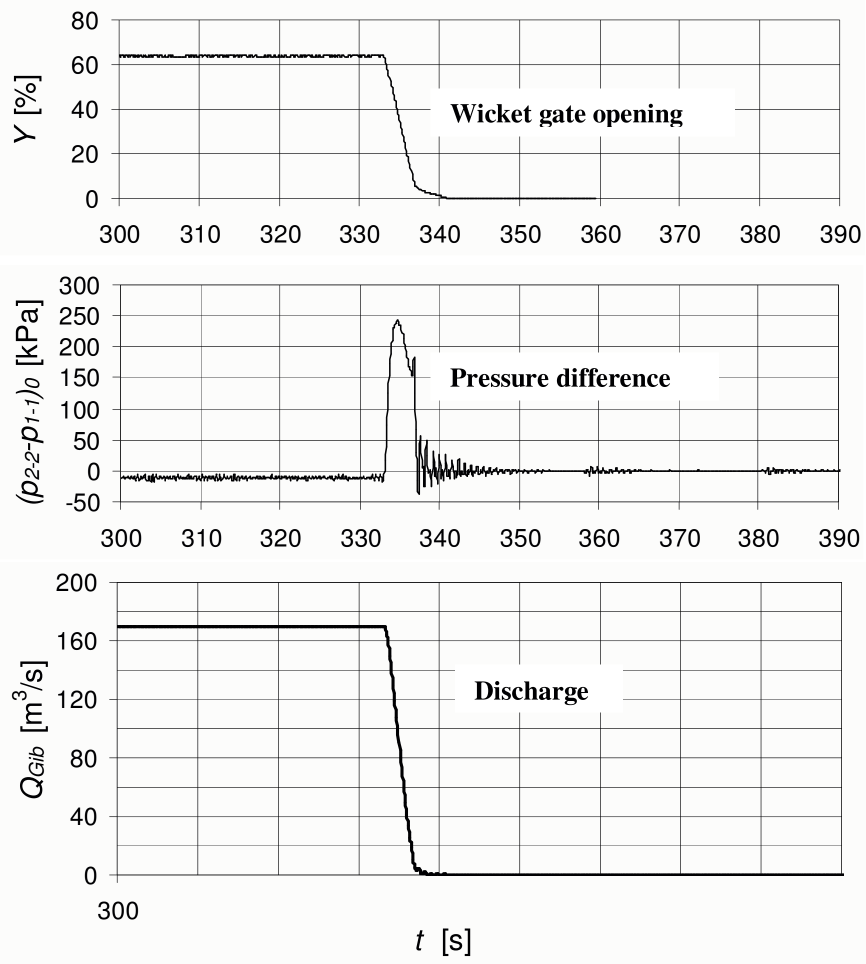

Fig. 11. Sample tested pressure difference between hydrometric section 1-1 and 2-2 of the water turbine penstock during stoppage of the flow, and the discharge calculated based on these data.

The performance characteristics of the tested turbine, was determined based on the measurements, are shown in Fig. 12. The power output on the turbine shaft (P_m) was determined from the electric active power measured in the generator terminals and using its efficiency characteristics, which were provided by the maker.

5 RESULTS OF CALIBRATION OF THE WINTER-KENNEDY METHOD MEASURING SYSTEM

The results of flow rate measurement performed using the Gibson method were used for calibrating another measuring system based on the Winter-Kennedy method. This method uses static pressure difference between the inner and outer side of the turbine spiral case, which is caused by the centrifugal force acting on the curved streams of fluid. The flow measurement performed with the aid of this method makes use of the following relation between the flow rate Q and the difference of the above named pressures $\Delta p = p_1\text{-}p_2$:

$$Q = K_{W-K} \cdot \Delta p^n , \tag{8}$$

where $K_{W\text{-}K}$ is a constant coefficient, which must be experimentally determined during calibration, and n is power exponent, theoretically equal to 0.5.

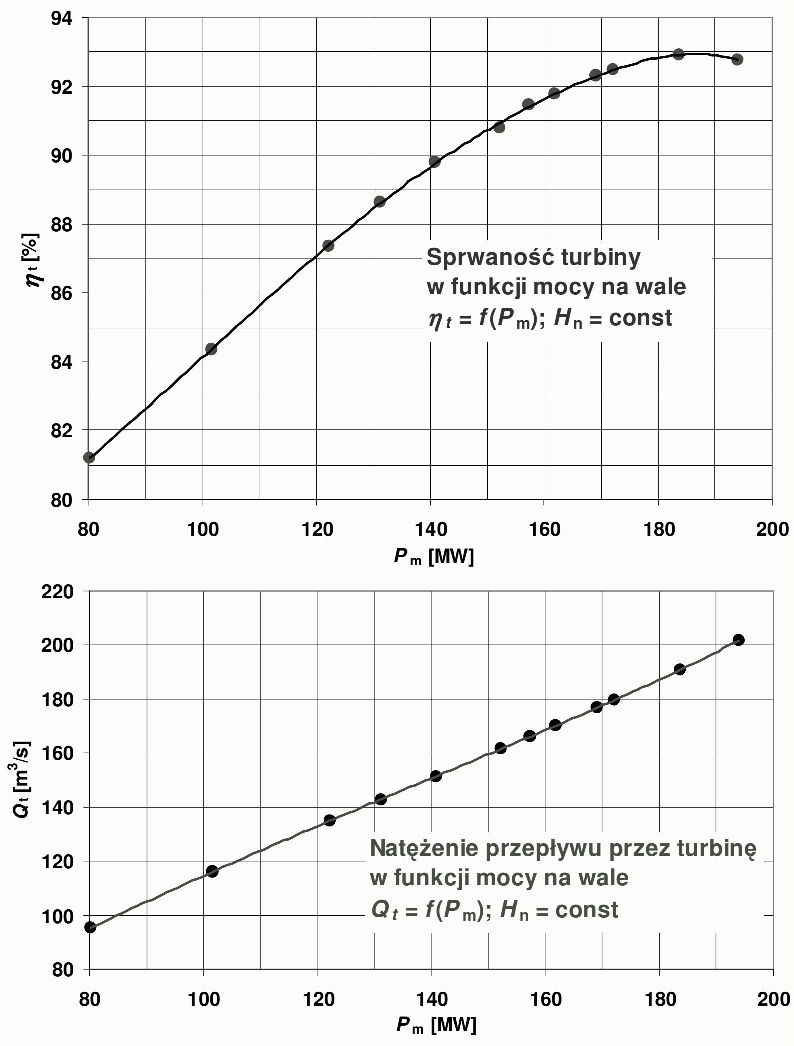

Fig. 12. Performance characteristics of the tested turbine.

Unlike the Gibson method, this method belongs to the group of relative (index) methods and can be used for efficiency tests of water turbines only after the calibration, making use of an absolute method. In order to secure correct results of the flow rate measurements, a careful selection of pressure reception orifices and correct measurement of the pressure difference between those points is needed. Once these conditions are met, we can expect that the accuracy of the measurements performed using the Winter-Kennedy method is close to the accuracy of the method used for calibration. The selection of the pressure taps should be based on recommendations included in relevant standards. The recommendations given by the international standard IEC 41-1991 [16], for a system with a steel turbine spiral case are shown in Fig. 13.

The pressure difference between the two selected points in the spiral case of the examined turbine was measured using a so-called smart pressure difference transducer, of accuracy 0.1%. The obtained results, which were used for calibrating the Winter-Kennedy system, are shown in Fig. 14. The constant coefficient $K_{W\text{-}K}$ was determined using the smallest square method applied to all results of flow rate measurements obtained with the Gibson method, and pressure differences in the spiral case.

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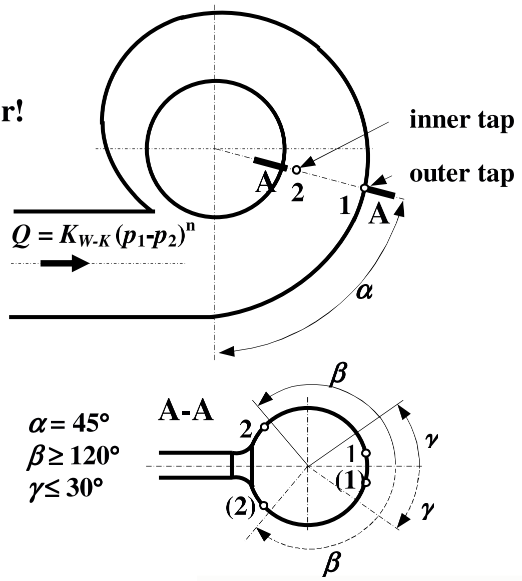

Fig. 13. Recommendations concerning the location of taps for Winter-Kennedy method of water flow rate measurement through a turbine equipped with a steel spiral case.

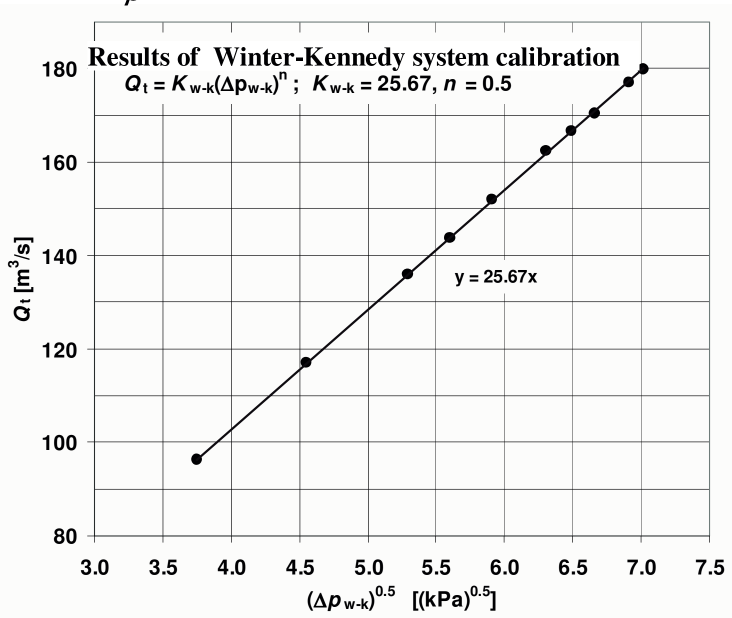

Fig. 14. Graphical presentation of the results used for calibrating the Winter-Kennedy measuring system, used in the tested turbine.

6. CONCLUSIONS

1. Due to the fact that the majority of water turbine penstocks have not access to external pipe walls, special instrumentation was developed which allows the flow rate measurement to be performed using the Gibson method in these conditions. The measuring instrumentation was developed in the IF-FM PAS, Gdansk, and successfully used in a number of large water power plants in Poland and Mexico.
2. In the examined cases, the efficiency measurements performed for one hydropower station head with the aid of the Gibson method, were used for determining the efficiency curve of the turbine and the hydro-unit, and for calibrating the measuring system based on the Winter-Kennedy method. Once calibrated, the Winter-Kennedy system can be used for continuous flow rate measurement and for determining turbine performance (efficiency) characteristics of for other power plant heads.

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