TRANSACTIONS OF THE INSTITUTE OF FLUID-FLOW MACHINERY

No. 123, 2011, 57–70

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A new approach to using the classic pressure-time method of discharge measurements

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Abstract

Discharge measurement using the pressure-time (Gibson) method typically involves mounting measurement instrumentation on the outside of the penstock. In the case of a hydropower plant where the penstock is built over concrete, an innovative approach is necessary in order to install instrumentation inside the penstock. Such instrumentation has been implemented for the purpose of efficiency tests of the upgraded small Kaplan turbine. The pressure-time method, in its classic version, requires sending pressure signals from both penstock cross-sections to the differential pressure transducer by means of connecting tubes. This raises the question on the influence exerted by dynamic properties of the connecting pipes/transducer system on the discharge measurement results. Calculations carried out using previously developed method enable authors to demenstrate that the connecting pipes/transducer system had exerted a negligible influence on the discharge measurement results.

Keywords: Hydraulic turbine; Penstock; Discharge measurement; Pressure-time method; Gibson method; Efficiency test

1 Introduction

The pressure-time method (Gibson method) utilises the water hammer phenomenon in a pipeline. This method found its main application in the measurement of flow rate in pipelines of hydraulic machines [1–4]. It is recommended by the international standard IEC 41:1991 as well as its European equivalent EN 60041 [1]. Under the measurement conditions recommended by the standard, the accuracy of measurement results is better than ±1.5–2.3% and it does not stay away from

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the accuracy of other basic methods for flow measurement (current meter, tracer and ultrasonic methods).

In practice, several versions of the pressure-time method are used. The most important ones are:

1. The *classic version* that relies on the direct measurement of the pressure difference between two hydrometric sections of the penstock by means of a pressure differential transducer, whereas the measuring penstock segment between the sections is straight and has a constant diameter.
2. The *version with separate penstock measurement sections* where a separate measurement of pressure-time variations in two hydrometric sections of the penstock is used.
3. The *version with single penstock measurement section* relying on the measurement of pressure variations in one hydrometric section of the penstock and referring these changes to the pressure in an open reservoir of the liquid to which the penstock is directly connected.

The paper presents experiences in application of the classic version of the pressure-time method (the first version mentioned above) that was used in the efficiency tests of the upgraded small Kaplan turbine. The turbine is fed by means of a 4 m diameter and about 40 m length concrete penstock. Under the normal condition of the considered case, the access from the outside to the turbine penstock is impossible, so the measuring instrumentation had to be installed inside the penstock after its emptying. The paper also presents the results of analysis of effect of dynamic parameters (time constant) of differential pressure transducer and the length of the impulse tubes connecting pressure-tapping points to the transducer on the discharge measurement results obtained using the pressure-time method. The previously developed computational code has been used to determine this effect [6].

2 Principles of the pressure-time method in its classic version

The pressure-time method is based upon the second law of dynamics (Newton's law) as applied to the decelerated mass of liquid stream flowing through the pipeline. The inertia force of the stopped liquid mass is manifested by the pressure difference between two different pipeline cross sections. The value of measured discharge is calculated by integrating the recorded pressure difference time-variation within a proper time interval.

The relation between pressure p and volumetric flow rate Q in two selected perpendicular cross-sections 1-1 and 2-2 of the pipeline with constant flow area A, distant along its axis by L (Fig. 1), can be expressed by the equation[1]:

$$p_1 + \rho g z_1 = p_2 + \rho g z_2 + P_f + \frac{\rho L}{A} \frac{dQ}{dt} \,, \tag{1}$$

where p_1 and p_2 are mean static pressures in hydrometric pipeline cross-sections 1-1 and 2-2, respectively, z_1 and z_2 – weight center elevations of hydrometric sections 1-1 and 2-2, ρ – water density, P_f – pressure drop caused by friction losses (hydraulic resistance) in the pipeline between sections 1-1 and 2-2. The last term of the equation represents the effect of liquid inertia in the considered pipeline segment of length L.

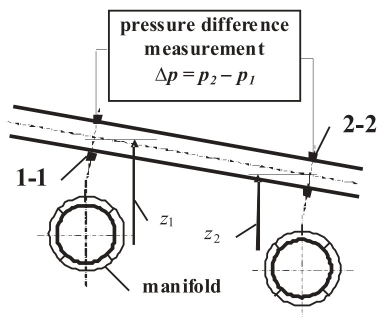

Figure 1. Pipeline segment with marked measurement sections used in the pressure-time method.

After integrating Eq. (1) in the time interval (t_0, t_k), in which the flow varies from the initial to the final value, the difference $(Q_k - Q_0)$ between these values can be derived. Assuming that the discharge value under final conditions is Q_k, i.e. the remaining discharge after closing up the shut-off device, we get an expression determining the discharge value in the initial conditions (before starting the transient process), Q_0, as follows:

$$Q_0 = \frac{A}{\rho L} \int_{t_0}^{t_k} \big[\Delta p(t) + P_f(t)\big]\, dt + Q_k \,, \tag{2}$$

[1]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. In the Eq. (1) the liquid compressibility is omitted as well as the pipe wall deformation due to the pressure change. As it can be observed from many evaluations, this simplification does not influence significantly the results of the flow rate measurement in flow systems of hydraulic turbines.

where $\Delta p = p_2 + \rho g z_2 - p_1 - \rho g z_1$ is the static pressure difference between sections 2-2 and 1-1, Q_k – discharge in the final conditions (usually the leakage rate through the cut-off device in the closed position).

It follows from Eq. (2) that the hydraulic losses P_f in the pipeline segment of length L should be separated from the measured variation of the static pressure difference (Δp) between hydrometric sections of the pipeline. Thus, we obtain the pressure rise resulting from the inertia force (momentum change) of the liquid in the considered segment of the pipeline. The value of hydraulic losses is calculated with satisfactory accuracy using its dependence on the discharge square.

3 Use of the pressure-time method in its classic version with the instrumentation installed inside the penstock

In the considered case, the efficiency tests of 4 MW turbine were considered using the classic version of the pressure-time method to measure the discharge. Both hydrometric sections 1-1 and 2-2 were located in a concrete cylindrical penstock segment of 4 m diameter – Fig. 2. Section 1-1 was located more than 8 m ($2D$) downstream the penstock inlet, and section 2-2 was situated about 14 m upstream the turbine spiral case inlet. The segment between sections 1-1 and 2-2 was straight and characterized by about 17 m length, constant pipe cross-section and lack of any significant irregularity. In each of these sections four pressure taps were uniformly located at the circumference – Fig. 3.

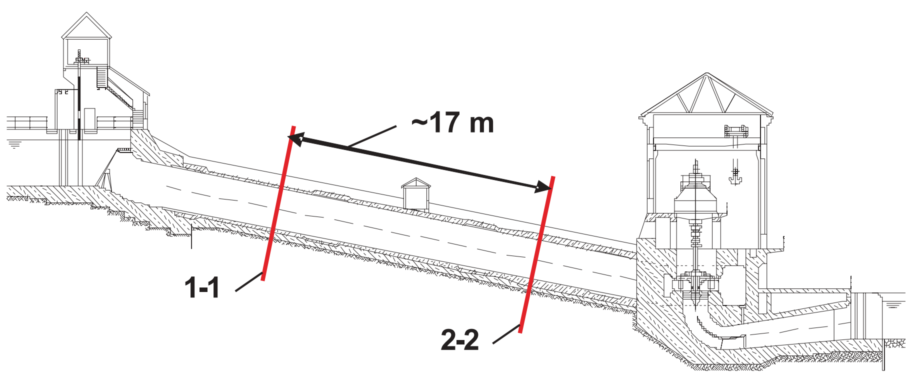

Figure 2. Layout of the flow system of the tested turbine with marked hydrometric sections used by the pressure-time method.

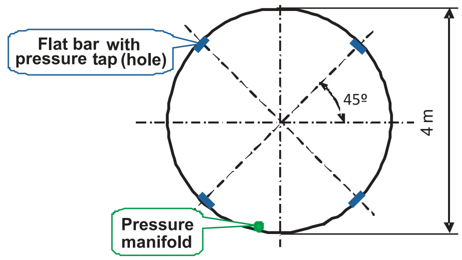

Figure 3. Distribution of the pressure holes in the penstock hydrometric sections 1-1 and 2-2.

Considering no access to the penstock from outside, internal pressure measurement devices were manufactured. Special flat bars (Fig. 4) with pressure holes were mounted to the internal side of the penstock concrete wall, in parallel to the water flow direction (pipeline axis). In order to reduce the influence of the installed flat bars on the streamlines distribution near the holes, the following conditions had to be fulfilled: 1) suitable shape of bar ends, 2) smooth surface of bars on their flow sides, and 3) correct location and geometry of holes in the bars. The problem is that the location of pressure receipt point, should not generate instabilities of liquid flow, mainly, the boundary layer separation and vortex formation. The bar thickness is determined both by the diameter of the pressure hole and the diameter of the connecting tube, whereas its length and profile are selected considering reduction of instability of the streamlines around the pressure intake point.

In each hydrometric section, the pressure holes were connected to the manifold by means of cooper impulse tubes – Fig. 5. The manifolds of both hydrometric sections were connected by means of impulse tubes to the tight housing with the differential pressure transducer installed inside – Fig. 6.

A precise differential pressure transducer with good dynamic properties was used in order to measure the pressure difference between the sections, upper (1-1) and lower (2-2). Technical parameters of this transducer were as follows:

- measurement range: (-20–20) kPa,
- precision class (basic error) 0.1%,
- time constant 0.01 s.

The electric signal from the transducer installed inside the penstock was sent to the computer data acquisition system by means of an electric conduit in a protective copper tube.

The static pressure difference between sections (1-1) and (2-2), measured by the transducer, was recorded as a time-history of variations by the computer data acquisition system. Recording was performed with sampling frequency of 500 Hz,

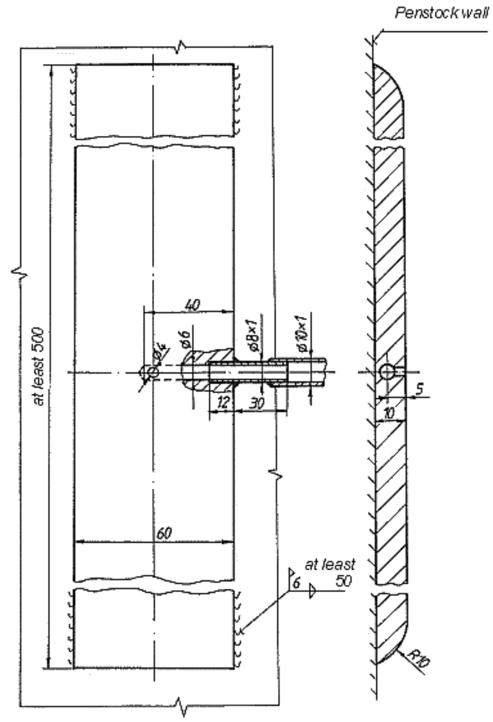

Figure 4. The flat bar used for pressure measurements.

and the input data files needed to calculate the flow by the pressure-time method were prepared in ASCII format with recording frequency of 100 Hz. Values of the measured discharge were determined by means of the *GIB-ADAM* software developed at the Szewalski Institute of Fluid-Flow Machinery PAS (IMP PAN) in Gdansk [7][2].

The discharge in the final conditions was the rate of leakage flow through the closed guide vanes of the tested turbine. It was determined based on the measurement of rate of water level decrease in the cylindrical segment of the penstock. For this purpose, pressure in the turbine spiral case and water level in the lower reservoir were measured. During this measurement the water gate at the penstock inlet was kept tightly closed and the gate at the exit of the draft tube was disassembled.

[2]The *GIB-ADAM* software is the main tool enabling the utilization of the pressure-time method in practice. The first practical application of this method was undertaken in Poland by the IFFM PAS, Gdansk, in the second half of 90 s. Since 1998, IFFM PAS has used different versions of the pressure-time method in numerous plants in Poland and in Mexico [8–11]

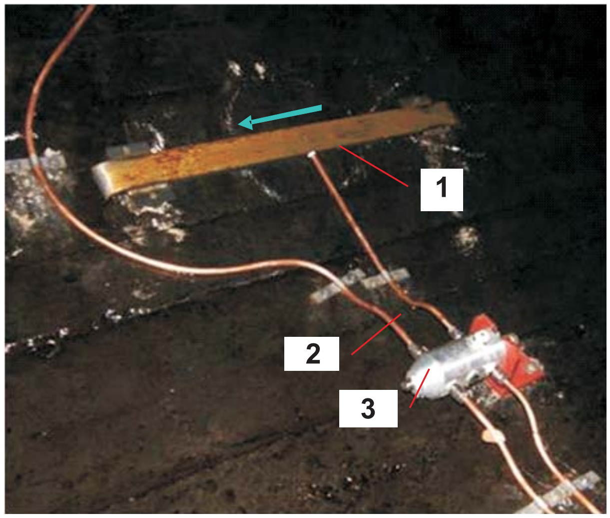

Figure 5. Measurement elements installed in the hydrometric section 1-1: 1 – flat bar with the receipt point for pressure measurement, 2 – impulse tubes and 3 – manifold collecting pressure from four holes.

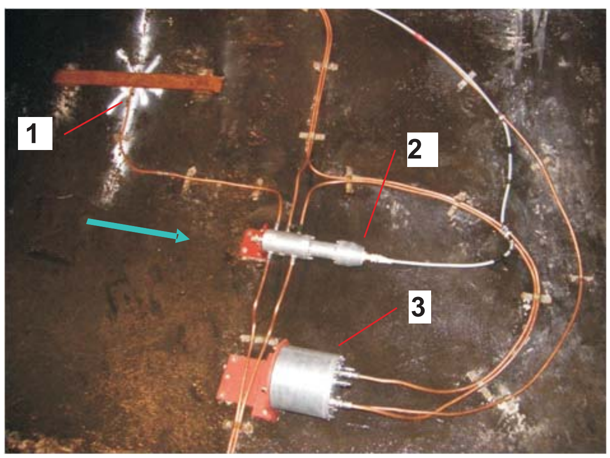

Figure 6. Measurement elements installed in the hydrometric section 2-2: 1 – flat bar with the receipt point for pressure measurement, 2 – manifold collecting pressure from four holes in section 2-2, and 3 – hermetic housing with the pressure differential transducer installed inside.

4 Results of turbine tests

Each test run was started after adjusting appropriate conditions of the tested turbine and after few minute stabilization of its operating conditions. During these runs, each flow rate measurement using the pressure-time method required relatively fast closure of the turbine wicket gate that stopped the water flow through the turbine. During wicket gates closure the generator of the unit was kept connected to the electric power grid. Figure 7 shows an example of the recorded wicket gate closure process and variation of pressure difference measured between hydrometric sections 1-1 and 2-2 of the penstock. Last chart in Fig. 7 presents the flow rate changes determined using the *GIB-ADAM* code applied to the recorded pressure difference variations.

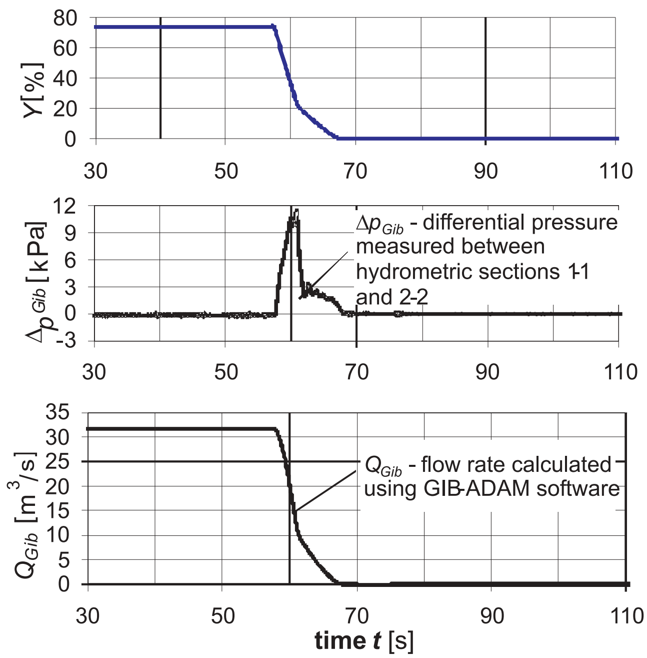

Figure 7. Time-history of recorded and calculated variations of parameters used for flow rate measurement by means of the pressure-time method.

Besides of the discharge measurement, the specific hydraulic energy of the turbine (net head) and the mechanical power were measured under stable flow conditions before the guide vanes closure. The performance characteristics of the tested turbines determined in result of measurements executed are shown in Fig. 8.

5 Effect of the impulse tubes and the pressure differential transducer on the discharge measurement results

The measurement and recording of the pressure difference variations are affected by a number of factors, e.g. the way of pressure input to the measurement trans-

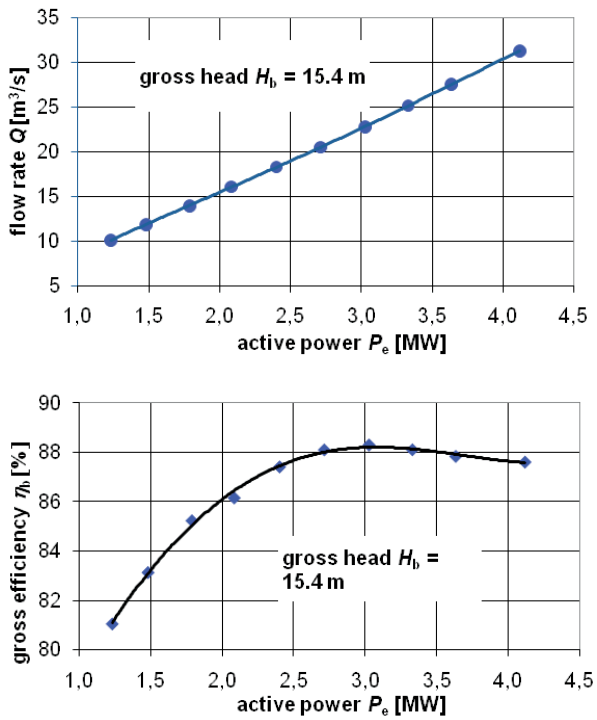

Figure 8. Hydro-set characteristics determined for one gross head. Test performed using the pressure-time method.

ducer, properties of applied transducer, accuracy of data recording devices and others. The influence of the first two factors on the flow rate measurement results is considered for the executed tests. The numerical code, developed especially for this purpose is based on the appropriate mathematical dynamic models of the differential pressure transducer and the impulse tube [6]. The main assumptions of these models are shortly presented below.

Model of pressure differential transducer The uncertainty of varying measurement signals is affected not only by the static characteristics of the transducer, but also by its dynamic properties. Assuming the transducer as the first order lag (inertia) element, the equation describing its dynamic behavior in the time domain is given in the following form [12]:

$$T_c \frac{dy}{dt} + y(t) = kx(t) \ . \tag{3}$$

By applying the control theories, its transfer function can be written as follows:

$$G(s) = \frac{Y(s)}{X(s)} = \frac{k}{sT_c + 1} , \tag{4}$$

where T_c means time constant, k is gain (amplification factor), x and y are, respectively, input and output signals, t is time, s means Laplace transform variable, X and Y mean Laplace transform of input and output signals, respectively. Figure 9 presents the model of transducer in the block form.

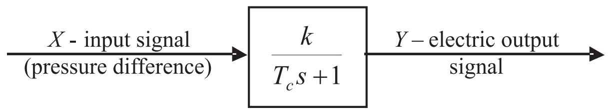

Figure 9. Block diagram of differential pressure transducer.

The correctness of the model choice has been confirmed by the special tests on *Rosemount* 1151 smart differential pressure transducer [6]. The tests were conducted for three time constants (T_c = 0.25, 0.85 and 3.2 s) after opening of the transducer cover in order to get an access to its membrane. For each time constant the test consisted in fast releasing of membrane prestrain during computer recording of the transducer output signal. Exemplary results of one of the tests are presented in Fig. 10 in the form of the recorded function of relative variation of transducer output signal for time constant $T_c = 0.25$ s, together with the transducer time response resulting from the simulation carried out for the same time constant. Good coincidence between the signals coming from the real transducer and the results of simulation based on the model described above has been achieved.

Model of impulse tube Assuming one-dimensional and linear theory, oscillating (wavy) motion of the liquid filling the impulse tube was described by the continuity and dynamic equations in the following forms, respectively [13]:

$$\frac{\partial \Delta V(x,t)}{\partial x} + \frac{1}{\rho a^2}\frac{\partial \Delta p(x,t)}{\partial t} = 0 , \tag{5}$$

$$\frac{1}{\rho}\frac{\partial \Delta p(x,t)}{\partial x} + \frac{\partial \Delta V(x,t)}{\partial t} + K_h \Delta V(x,t) = 0 , \quad K_h = \frac{32\mu}{\rho D^2} , \tag{6}$$

where x is a length coordinate along the pipe, t – time, ΔV – liquid velocity rise (fluctuation) referred to the average value, Δp – pressure rise (oscillatory) from its average value, D – internal tube diameter, ρ – liquid density, g – acceleration of gravity, a – pressure wave speed, μ – dynamic liquid viscosity. The last term

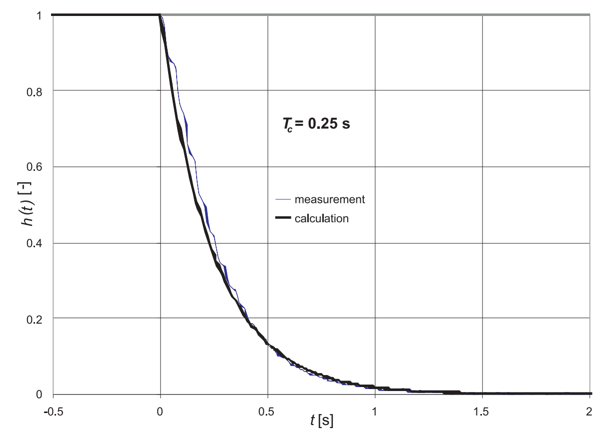

Figure 10. Comparison of the real time response of Rosemount 1151 Smart pressure transducer to the step function and the time response obtained from the simulation based on considered model.

in Eq. (6) represents hydraulic resistance (friction losses) for the case of laminar liquid flow inside the impulse pipe.

An operational method [14] was used to solve the closed system of Eqs. (5) and (6). That, after applying the Laplace transform at zero initial condition ($\Delta p(x,0)=0$, $\Delta V(x,0)=0$), takes the following form:

$$\frac{\partial \Delta V(x,s)}{\partial x} + \frac{1}{\rho a^2} s \Delta p(x,s) = 0 , \tag{7}$$

$$\frac{1}{\rho}\frac{\partial \Delta p(x,s)}{\partial x} + s\Delta V(x,s) + K_h V(x,s) = 0 . \tag{8}$$

The computational method in the form of the computer program [6], previously developed in MATLAB/Simulink, has been applied in order to estimate the influence exerted by dynamic properties of the impulse tubes/differential pressure transducer system on the discharge determined by means of the pressure-time method in its classic version. A flow chart of the program is presented in Fig. 11.

Basing on the computations by means of the above mentioned computational code, negligible influence of the impulse piping/transducer system dynamics on the discharge measurement results has been stated for the pressure-time method application under consideration – Fig. 12. In the considered case where the time constant of the transducer is very short ($T_c = 0.01$ s), the discharge calculated for the measured pressure variation differs not more than 0.1% from the discharge calculated for the same variation using the code descriebed above which takes into account dynamic properties of transducer and connecting pipes.

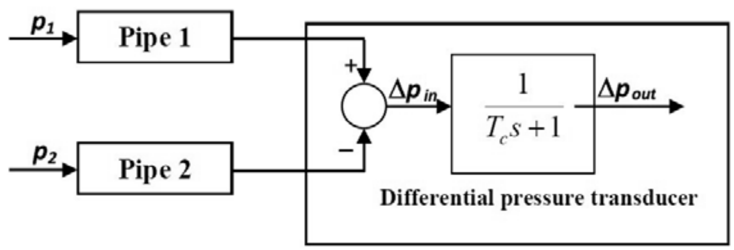

Figure 11. Flow chart of the developed program: p_1 – pressure in hydrometric section 1-1, p_2 – pressure in hydrometric section 2-2, p_{in} and p_{out} – input and output signal of differential pressure transducer.

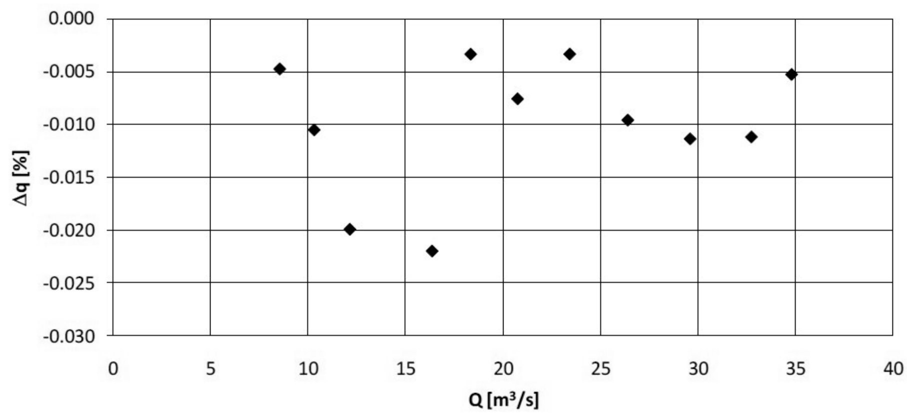

Figure 12. Influence of the impulse piping/transducer system on the determined flow rate (Δq – relative flow rate deviation from the value calculated without taking into account dynamic properties of transducer and impulse pipes).

6 Conclusions

1. The pressure-time method was developed and used in its classic version consisting in the direct measurement of pressure difference between two hydrometric sections of the penstock during closure of the turbine guide vanes. Because of the lack of accesss to the penstock from outside it was necessary to develop the special measurement instrumentation. The authors of this paper have not found a description of such an application methodology in the literature concerning this subject.

2. After upgrading, the performance characteristics of the small Kaplan turbine (4 MW) fed by the penstock were determined using for the flow rate measurement the developed classic version of the pressure-time method with instrumentation installed inside the penstock of 4 m diameter.

3. The influence exerted by dynamic properties of the connecting tubes/transducer system on the obtained discharge measurement results has been estimated using the previously developed computational method (computer program). Following the conducted calculations the tubes/transducer system has been found to exert a negligible influence on the discharge measurement results.

Received 29 April 2011

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