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# Discharge Measurement Techniques in Hydropower Systems with Emphasis on the Pressure-Time Method

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## 1. Introduction

Volumetric flow rate (discharge), as the volume of liquid flowing in time unit, belongs to the group of a few basic quantities needed to determine the hydraulic performance characteristics of hydraulic turbines and pumps. Discharge always represents the most difficult quantity to measure and accuracy (uncertainty) of its measurement is worse and very difficult to estimate in comparison with the power and head (or specific hydraulic energy). Despite immense progress in discharge measurement techniques, this part of the hydraulic machine performance tests is often a major challenge even for experienced test teams.

Besides the volumetric method, there are only a few primary methods of the absolute discharge measurement in hydropower plants, generally: (1) velocity-area method (local velocity distribution method), (2) pressure-time (Gibson) method, (3) tracer method, (4) ultrasonic method (ultrasonic flow meters), and (5) electromagnetic method (electromagnetic flow meters). Three first methods belong to the group of traditional (classic) methods, while the fourth one, the ultrasonic method, is relatively new and has been recently the object of numerous research activities oriented on its improvement and validation. This method has not yet reached the proper acceptance among the specialists. However, its basic advantage is the possibility of using it for continuous flow rate measurement. Electromagnetic method reveals also this advantage, however application of electromagnetic flow meters is limited to the conduits of small diameters, for instance up to 2 m. Because of some other advantages, electromagnetic flow meters are widely used in auxiliary water and oil systems of the hydropower plants.

After brief review of discharge measurement techniques, later on the recent important achievements in developing and utilizing the pressure-time method, as one of the primary method for measuring the discharge through the hydraulic machines, is presented. Nowadays, the pressure-time method is more and more frequently used in the hydropower plants equipped with penstocks longer than 15-20 m.

## 2. Background on flow rate measurement

### 2.1 Discharge measurement in small closed conduits

Measurement of fluid flow rate in conduits with small diameters, for instance up to 1 m, is not a very difficult task. Typical, standard measuring devices, such as constriction flow meters (measuring orifice plates – Fig 1, flow nozzle – Fig 2 or Venturi tube – Fig 3) and calibrated pipe elbows (bends) – Fig. 4, are used in such conduits. These devices are usually mounted in a properly prepared measuring segment of the conduit. They belong to the group of measuring devices using pressure difference  $\Delta p$  which nowadays can be measured with high accuracy. The flow rate is expressed as a function of the measured pressure difference:

$$Q = f(\Delta p) \quad (1)$$

These devices are highly reliable, however they are very sensitive to flow pattern and cause relatively high pressure drop due to hydraulic resistance, especially in cases of measuring orifices plates.

The principle of the constriction flow meter operation is based upon the Bernoulli equation, which can be written in the form:

$$p_1 + 0.5\rho V_1^2 + \rho g z_1 = p_2 + 0.5\rho V_2^2 + \rho g z_2 \quad (2)$$

and the following continuity equation:

$$V_1 A_1 = V_2 A_2 = Q \quad (3)$$

where  $p$  means the pressure,  $V$  – flow velocity,  $\rho$  – liquid density,  $g$  – gravity acceleration,  $z$  – elevation,  $Q$  – flow rate,  $A$  – flow area ( $A_1=0.25\pi D^2$ ,  $A_2=0.25\pi d^2$  – see Figs. 1, 2, 3) and the indexes “1” and “2” denote the cross sections before and within the considered constriction, respectively. Combining Eq. (2) and Eq. (3) after introducing the static pressure difference before and within the constriction (after relating both to the same elevation),  $\Delta p=p_2+\rho g z_2-p_1-\rho g z_1$ , we can get the following formula:

$$Q_{ideal} = \left( \frac{2\Delta p}{\rho} \right)^{0.5} \frac{A_2}{\left( 1 - \left( \frac{A_2}{A_1} \right)^2 \right)} \quad (4)$$

The above formula applies only to flows of the so called perfect (ideal) liquid. For real liquid flow, viscosity and turbulence are present and act to convert kinetic flow energy into heat. In order to take this effect into account, a discharge coefficient  $C_d$  is introduced to reduce the flow rate

$$Q = C_d Q_{ideal} \quad (5)$$

The discharge coefficient  $C_d$  has different values depending on the kind of the measuring device and its geometry. The value of  $C_d$  has to be experimentally determined. For the standard Venturi tubes the discharge coefficient  $C_d$  ranges from 0.93 to 0.97, however, for

the standard orifice plates its value is close to 0.6. The flow nozzles are shortened versions of the Venturi tube, with lower pressure drops than orifice plates. It means that the orifice plates, causing much higher energy losses than the Venturi tubes and flow nozzles, should not be widely used for measuring the flow rate in pipelines, especially in large ones.

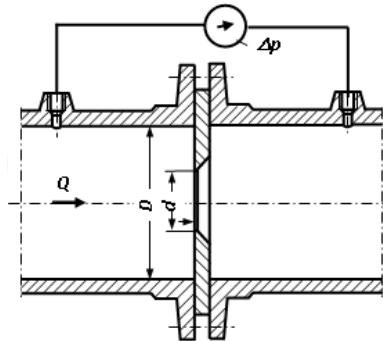


Fig. 1. Orifice plate.

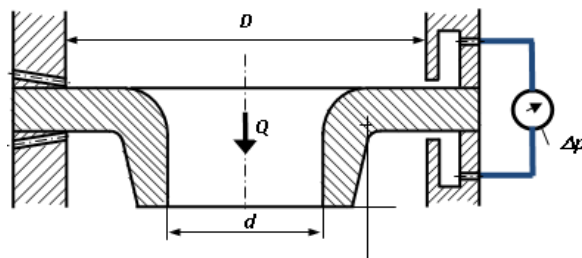


Fig. 2. Flow nozzle.

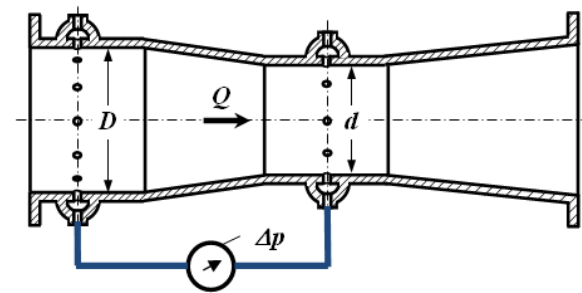


Fig. 3. Conical-type Venturi tube.

The calibrated elbows belong also to the group of flow meters based on pressure difference measurement. When liquid flows through the pipe elbow, the centrifugal forces cause a pressure difference between the outer and inner sides of the elbow,  $\Delta p = p_2 - p_1$  – Fig. 4. This pressure difference is used to calculate the pipe flow velocity  $V$  or flow rate  $Q$ . The simplified relationship between  $V$  and  $\Delta p$  can be written in the following form:

$$\Delta p = \rho \frac{D}{R} V^2 \tag{6}$$

The pressure difference generated by the elbow flow meters is smaller than that caused by other pressure differential flow meters, presented above, but the elbow flow meters have less obstruction to the flow.

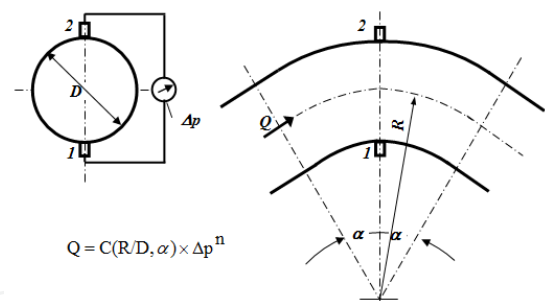


Fig. 4. Elbow flow meter.

The measuring devices briefly presented above can be easily used for continues measurements of flow rate, that is very important in different kind of monitoring hydraulic systems. The relevant pressure transducers have to be applied to achieve such goal.

Other devices are also available, such as electromagnetic flow meters (Fig. 5) and different kind of ultrasonic flow meters that are shortly described in the farther part of this chapter.

The electromagnetic flow meters are based upon Faraday’s law of induction, e.g. use the phenomenon of inducing electromagnetic force caused by flow of conducting fluid. The phenomenon can be described in the form of following relationship:

$$U_E = VBL \tag{7}$$

in which  $U_E$  means the induced voltage (voltage generated in a conducting liquid),  $V$  - the average liquid velocity,  $B$  - the magnetic field strength,  $L$  - the distance between the electrodes - see also Fig. 5.

The main advantages of the electromagnetic flow meters can be expressed as follows: They do not disturb the flow pattern and do not cause the pressure losses (drops), and also, are not very sensitive to the wear, and can be easily used for continues measurements of flow rate. Such instruments are produced as measuring segments that are installed into pipelines of different diameters, up to 2 meters. Nowadays, due to their many advantages, they are very often used in hydropower plants, mainly in auxiliary water and oil systems. Unfortunately, the author of this chapter does not know any case of electromagnetic flow meter application in turbine penstocks of several meter diameter.

The international standards ISO 6817 and ISO 9104 relate to the flow rate measurements using the electromagnetic meters.

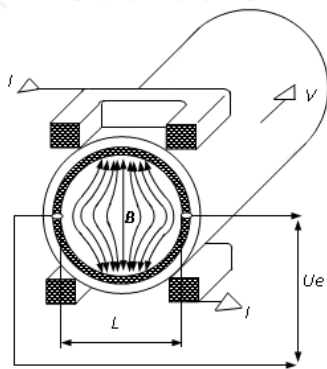


Fig. 5. Electromagnetic flow meter.

2.2 Flow rate measurement in small open conduits (channels) – free-flow meters

The free-flow meters (Fig. 6) consist in raising the head of the liquid stream and relating the discharge to the head accordingly to the theoretical or experimental formulas. The flow rate ( $Q$ ) is expressed as a function of the head over the weir ( $h$ ):

$$Q = f(h)$$

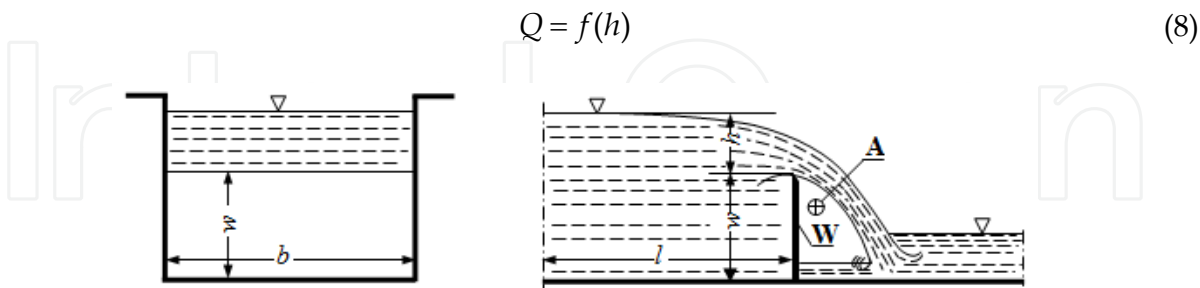


Fig. 6. Measuring weir. W – weir plate, A – ventilation duct.

Rectangular weirs (Figs. 7 and 8) are the most commonly used weirs in hydrometric practice. We can distinguish rectangular weirs without end contractions (Fig. 7) from rectangular weirs with end contractions (Fig. 8), where the width of the crest is less than width of the approach channel  $b < B$ . There are also free-flow meters with variable-flow area, i.e. the ratio of their throat cross-section  $A_c$  to their inlet cross-section  $A$  change with the flow rate ( $A_c/A$  varies with discharge  $Q$ ).

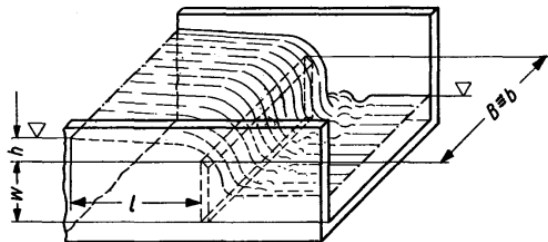


Fig. 7. Rectangular weir (without end contractions) - Hansen weir.

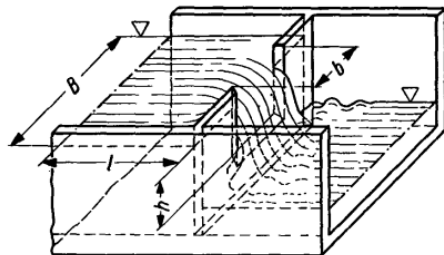


Fig. 8. Rectangular weir with double end contractions - Poncelet weir.

The accuracy of these measuring devices is dependent mainly on the error of measurement of the head over the weir. There are some other factors having important influence on the accuracy, e.g. quality of weir plate and walls, and flow velocity distribution at the inflow side.

The standard ISO 1438-1 relates to the water flow rate measurements in open channel using weirs.

### 3. Brief review of primary methods for discharge measurement in hydropower systems

The devices presented above are not generally suitable for water discharge measurements in large-dimension conduits, having the diameter of an order of several and more meters. Measurements of discharge in these conduits, frequently used in hydropower engineering, are very difficult and expensive. Preparation and performance of high accuracy measurements is even more difficult by (1) hydro-technical conditions of the power plants (very large real objects, during erection of which the aspects of the use of measuring methods are often neglected) and (2) high requirements referring to the operating conditions of the hydro-units in the electric power system (for instance, very high costs of possible machine stoppage to install the measuring systems – the machine standstill cost is often higher than the cost of preparation and performance of measurements). Additionally, it is still expected to measure water discharge in hydropower with higher precision, for instance, at present within systematic uncertainty of  $\pm 1\%$ .

There are only a few primary methods of the absolute discharge measurement in hydropower plants:

1. The **velocity-area method** [ISO 3354, ISO 7194, ISO 3966] utilizes the distribution of local flow velocities, measured using mainly propeller current meters (Fig. 9) - in cases of large conduits - or impact pressure velocity meters (Pitot static tubes, Fig. 10) - for smaller conduits and clean water. The volumetric flow rate is determined by integrating this distribution over the entire area of the measuring section.

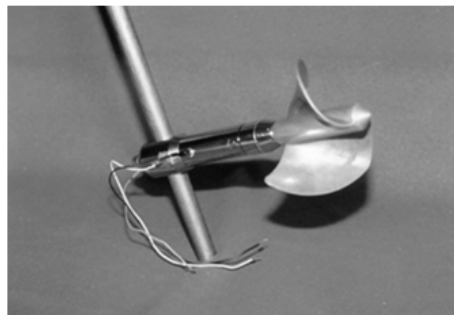


Fig. 9. Propeller-type current meter. (The local flow velocity component is measured based on the current meter rotor revolutions counted in a given time period, and the experimentally determined relationship between the current meter rotation speed and local flow velocity).

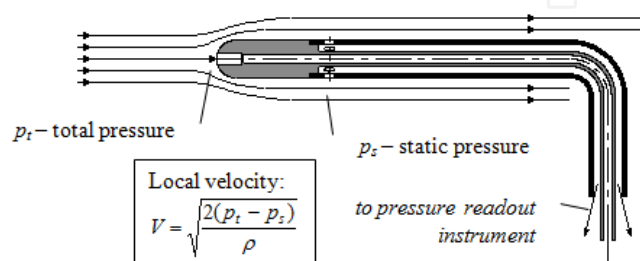


Fig. 10. Pitot static (Prandtl) tube. (The local velocity is resulted from the dynamic pressure measured as the difference between the total (stagnation) pressure and the static pressure).



2. The **pressure time method** (water hammer or Gibson method) [IEC 60041, IEC 62006, ASME PTC 18] is based on measuring the time-history of pressure difference changes between two hydrometric sections of the closed conduit during a complete stop of the fluid flow by means of the shut-off device. The volumetric flow rate of the liquid in the initial conditions, before the stream has been stopped, is determined from relevant integration of the measured pressure difference change occurring while stopping the liquid stream.
3. The **tracer method** [IEC 60041] consists in measurements of the passing time, or concentration, of radioactive or non-radioactive substance (salt, for instance) between two sections of the penstock. The method requires long conduits and conditions for good mixing of the marker.
4. The **ultrasonic method** [IEC 60041] uses the principles of ultrasound and is based on vector summation of the ultrasound (acoustic) wave propagation velocity and the average flow velocity – the use of difference in frequencies or passing times of the emitted and received acoustic signal. Ultrasonic transducers with special software are used for realization of discharge measurement according to rules of this method. The basic advantage of the method is the possibility of its use for continuous discharge measurement. Other primary methods do not reveal this advantage.

The electromagnetic method, mentioned as a fifth one in the introduction, is not considered here due to its application limited to flow measurement in small pipelines.

Three first aforementioned methods belong to the group of traditional (classic) methods, while the fourth method, the ultrasonic method is still the object of numerous research activities oriented on its improvement (Gruber, 2008, Gruber at al., 2010; Hulse at al., 2006; Llobet at al., 2008; Nichtawitz at al., 2004; Strunz at al., 2004; Tresch at al., 2006). Ultrasonic flowmeters are affected by the distribution of flow velocity, turbulence, the temperature, density and viscosity of the flowing medium and the presence of gas bulbs. There is still main question: Is the velocity measured by the ultrasonic meter equal to the average flow velocity along the path of an emitted beam of ultrasound? The relevant integration methods are still developed (Gruber at al., 2010). The ultrasonic method has not reached proper acceptance among the specialists yet. The IEC 60041 standard suggests conditional use of this method, i.e. in cases of explicit agreement of all contracting parties.

Author's own experiences based on multiple verification tests of ultrasonic flow meters, as well as their application, confirm the existence of the above mentioned problems. These problems in many cases make it impossible to obtain measurement results of desired accuracy and reliability using ultrasonic flow meters. On the other hand, basing on many publications in this topic, it can be confirmed that in specially prepared conditions, mainly in the laboratory, tested ultrasonic flow meters give a surprisingly good agreement comparing with other flow measurement techniques. Very often the differences do not exceed (0.5-0.7)%. These divergent assessments point to the need for scientific research of the ultrasonic method of flow measurements, which should be conducted in various real conditions.

The tracer method is the least popular among the above mentioned classic methods. It requires very long measuring segments and special, additional conditions facilitating the mixing process of the introduced marker, the use of turbulizers, for instance.

It should be stressed here that at present the primary methods of absolute discharge measurement in turbine penstocks include the velocity-area method and the pressure-time



(Gibson) method. It is also noteworthy that the velocity-area method, mainly making use of propeller current meters and most frequently used in waterpower engineering in the past, is nowadays being replaced by the pressure-time method in the hydropower plants equipped with penstock longer than 15-20 m. The reason for this is much lower cost of preparation and performance of the measurement based on the pressure-time method. Additionally, the development of computer techniques in recent twenty years has facilitated the measurements and provided opportunities for obtaining higher accuracy of the results using this method.

The different situation is for the low and very low head power plants with short intakes of water turbines. Up to now, generally only the velocity-area method is available in such kind of plants. Local velocities can be measured using various instruments, including current-meters, Pitot static tubes, and recently electromagnetic and ultrasonic meters. The discharge measurements using the velocity-area method is still unprofitable. This reflects that in the past the measurements have been performed only in the minority of low head power plants. Also, an alternative acoustic scintillation method, which allows to scan the flow measurement section, is still expensive and very sensitive to flow disturbances (Llobet et al., 2008).

Discharge measurements in low-head installations are linked with lack of sufficiently long straight flow channel, allowing for parallel streamlines, perpendicular to the hydrometric section. Usually, due to various reasons, the plane of stoplog hollows (Fig. 11) is considered as the optimum one. On the one hand side, such a location enables mounting current-meters on a traversing frame that results in high density of the local measurement points. On the other hand problems linked with deviation of the streamlines from direction perpendicular to the hydrometric section plane occur. Under such circumstances the use of CFD flow analysis in order to determine the streamline deviation angles is of essential significance.



Fig. 11. Frame with fixed the current meters for traversing the hydrometric (measuring) section (author's application).

Application of CFD calculations is highly recommended also in cases of measuring discharge with current-meters installed in short intake penstocks of hydraulic turbines - Fig. 12-13. Figure 14 shows a framework with current-meters situated along the calculated streamlines.

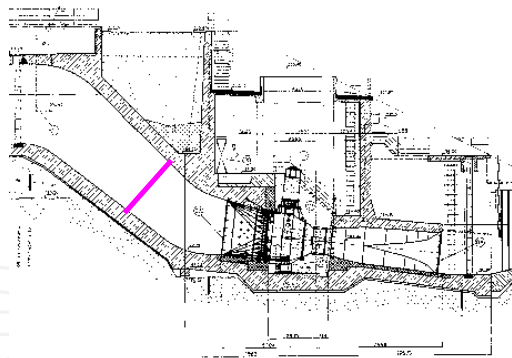


Fig. 12. Vertical section of the short penstock of the bulb turbine with hydrometric section indicated (own application).

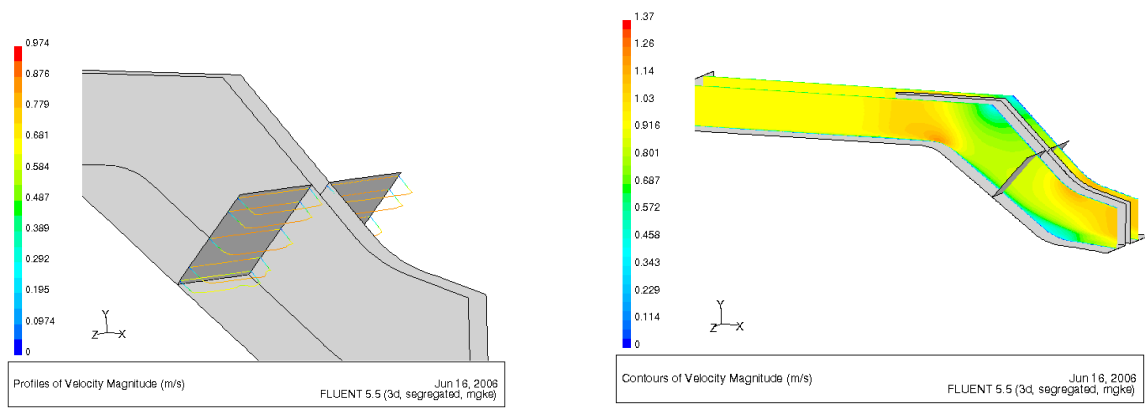


Fig. 13. Results of CFD calculations of velocity distributions in the considered case (own application).



Fig. 14. Hydrometric section with the supporting frame and installed current-meters (own application).

Generally, other methods and devices, like the standardized weirs, the differential pressure devices and the electromagnetic flow meters, described earlier, as well as the volumetric method, are also possible to use in hydropower plants for absolute discharge measurement [IEC 60041]. However, these methods have very limited area of application - they can be used mainly for small hydropower plants, not for large-scale discharge measurements. The volumetric method, conventionally confined to low flow rates, because of the size of the

reservoirs required, can be used in some large hydropower plants, particularly in pumped-storage plants with big artificial reservoirs but only when the characteristic (geometry) of these reservoirs are exactly known.

Discharge measurement using the volumetric method consists in determining the rise of water volume  $\Delta V$  in the head or tail water reservoirs during the measured period of time,  $\Delta t$ , as it can be written in the following form:

$$Q = \frac{\Delta V}{\Delta t} = \frac{V(z_0 + \Delta z(t)) - V(z_0)}{\Delta t} \quad (9)$$

where  $z_0$  means the water level at the initial conditions, at the test beginning.

The water volume rise  $\Delta V$  is determined by means of measurement of water level increment  $\Delta z$  during the test and the function  $V(z)$  known from the geometry of reservoir.

Some experiences of the author of this chapter concerning application of the volumetric method allow to indicate a few important problems (issues) relating to the accuracy of the relationship between water level and reservoir volume and the accuracy of measurement of water level rise (Adamkowski, 2001, Adamkowski et al., 2006). The reservoir volume should be determined by precise standard geometrical measurement or by photogrammetry. Practically, the required accuracy of such measurement can be only obtained for the concrete artificial reservoirs. Water level cannot be accurately measured using the instruments commonly used in the control system of the plants because very often they have much too high range and much too low precision class, additionally also various disturbing effects do not ensure the required accuracy of the measurements. Therefore the change in water level has to be determined using the special method [ISO 60041].

Fig. 15 presents an effective technique developed and applied by the author of this chapter for precise measurement of water level rise (Adamkowski, 2001). The technique was successfully utilized during the efficiency tests with the aid of the volumetric method in the Polish pump-storage power plants. Water level rise  $\Delta z$  is determined by measuring the difference between pressure in the hydropower plant water reservoir and the constant pressure in the auxiliary tank underhung at constant height during the tests. For this purpose, the differential pressure transducer of high precision class has to be connected to the plant reservoir and auxiliary tank.

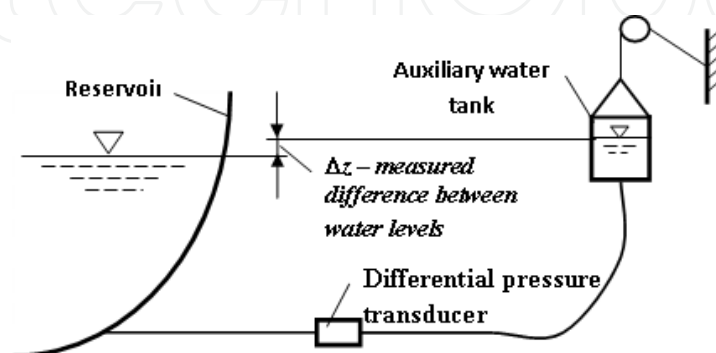


Fig. 15. Technique of water level rise measurement applied in the volumetric method in a few Polish pumped-storage power plants (own application).

Wave motion of water in the reservoir is one of factors that absolutely should be taken into consideration as the effect most affecting the measurement results. Computer data acquisition system and regression line (function calculated using the least squares method) applied to the recorded water level values can allow to eliminate the water waves disadvantageous effect – Fig. 16. Traditional readings realized in such kind of method do not give any chance for obtaining the required accuracy of discharge measurements.

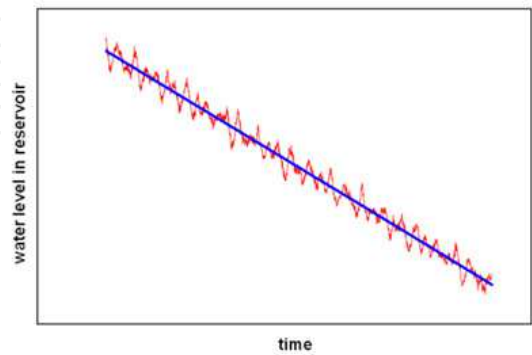


Fig. 16. Example of recorded water level signal and its regression line (own application).

**4. Pressure-time (Gibson) method of discharge measurement**

**4.1 The physical principles of the pressure-time method**

The pressure-time method (popularly called “Gibson method”) utilizes the inertia force effect which manifests in the pressure rise during deceleration of liquid mass flowing in a closed conduit (penstock in hydropower plant). The method is based on recording the time-history (time diagram) of pressure difference changes between two hydrometric (measuring) cross sections of the conduit during a complete stop of the fluid flow realized by means of the shut-off device. Fig. 17 shows a scheme of turbine penstock with marked measuring sections relevant to pressure-time method use. The volumetric flow rate of the liquid in the initial conditions, before full stop of the stream, is determined from proper integration of the measured pressure difference change during closing up the shut-off device installed in the penstock - pressure difference caused by inertia force. It can be proved that the area between the pressure difference time-history curve recorded during the transient state and the curve representing the hydraulic loss in the conduit segment (and the dynamic pressure difference between the end sections of this segment) is proportional to the change of the volumetric flow rate between the initial and final conditions – Fig. 18.

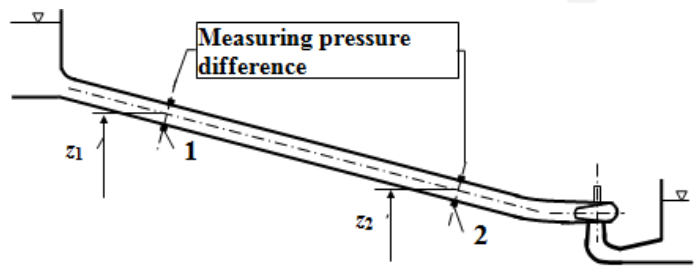


Fig. 17. Schematic layout of turbine penstock with marked measuring cross sections applicable for use in the pressure – time method.

#### 4.2 Basic information about the pressure-time method

The method was introduced in the first half of the 20th century (year 1923) by Norman R. Gibson (Gibson, 1923, 1954). (That is why it is called, after its author, the Gibson method). This method has been mainly used for measurements of discharge in the penstocks of water turbines and pump-turbines. It is recommended by the international standards IEC 60041 and IEC 62006 and the American standard ASME PTC 18. It is assumed that in the conditions consistent with the recommendations of these standards, the measurement accuracy is not worse than  $\pm(1.5-2.0)\%$  and does not differ from that represented by other primary methods, the current meter method, for instance.

The Gibson method was more frequently used in the North America than in Europe and in other parts of the world, especially when the optical techniques were employed to record pressure changes and combined with the manual graphical integration. Nowadays, the increased accuracy of pressure measurement instruments, along with the availability of the hardware for computer acquisition and processing of the measured data are the reasons why this method is becoming more attractive also all over the world. For example, during the latest two decades the method was extensively and successfully used in the performance tests of hydrounits that were carried out at many hydropower plants in Poland (Zarnowiec, Solina, Dychow, Zydowo, Niedzica, Koronowo, Zur, Pilchowice), as well as in Mexican hydropower plants (Angostura, Infiernillo, Chicoasen, Aquamilpa, Temascal, Villita, Infiernillo, Villita, Cobano, Novillo, Santa Rosa, Bacurato). In this period, the author of this chapter actively participated in developing process of the method in different kind of its aspects (Adamkowski & Kwapisz, 2000; Adamkowski at al., 2006a, 2006b and 2006c, 2007, 2008, 2009; Adamkowski & Janicki, 2007, 2008, 2009, 2010; Urquiza at al., 2007).

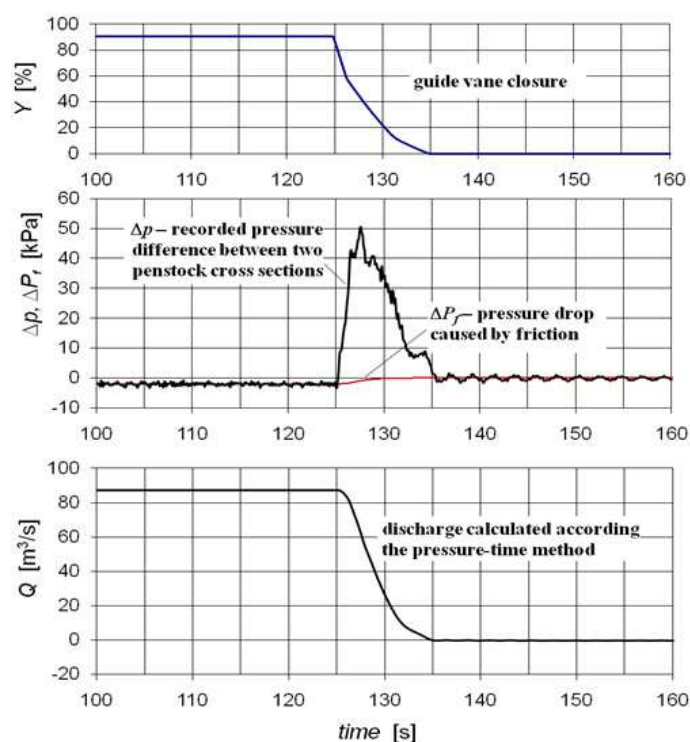


Fig. 18. Example of measurement of discharge through a turbine using the pressure-time method (own experiment).



### 4.3 Theoretical principles of the pressure-time method

In order to derive the relationship for calculating flow rate  $Q$  let us consider the closed conduit with the cross section area  $A$  changing along its longitudinal axis – see Fig. 19. In this conduit the stream of liquid is stopped. Let us extract from this conduit a segment of a length  $L$  between cross sections 1-1 and 2-2.

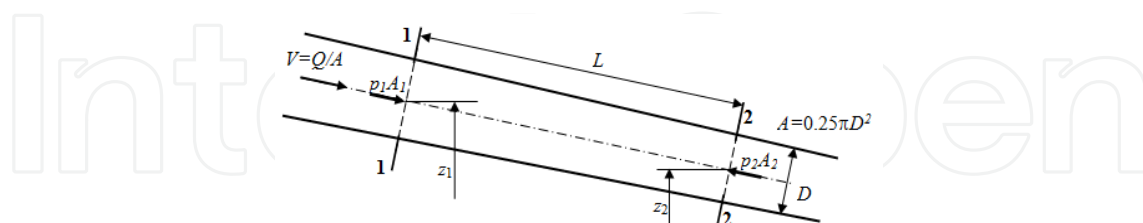


Fig. 19. Segment of a closed conduit with marks needed to explain the theoretical basis of the pressure-time method.

Let us farther assume that the liquid velocity and pressure distributions are constant in these sections, and that the liquid density and the flow section area do not change due to pressure variations.

According to these assumptions, the dependence between the parameters of the one-dimension unsteady flow in two selected cross sections of the conduit can be described using the energy balance equation, well known from the literature in the form:

$$\alpha_1 \frac{\rho Q^2}{2A_1^2} + p_1 + \rho g z_1 = \alpha_2 \frac{\rho Q^2}{2A_2^2} + p_2 + \rho g z_2 + \Delta P_f + \rho \int_0^L \frac{dx}{A(x)} \cdot \frac{dQ}{dt} \quad (10)$$

where  $\rho$  denotes liquid density,  $p_1$  and  $p_2$  present static pressures in pipeline cross sections 1-1 and 2-2, respectively (see Fig. 17),  $z_1$  and  $z_2$  are levels of 1-1 and 2-2 hydrometric pipeline section weight centres,  $\alpha_1$ ,  $\alpha_2$  are the Coriolis coefficients (kinetic energy correction coefficients) for 1-1 and 2-2 sections, respectively,  $Q$  is the volumetric flow rate (discharge),  $g$  means gravity acceleration and, finally,  $\Delta P_f$  is the pressure drop due to friction losses between 1-1 and 2-2 cross sections.

The last but one term on the right-hand side of the above equation represents hydraulic (friction) losses. In the discussed method the pressure drop due to these losses is determined from the following square discharge function:

$$\Delta P_f(t) = K_f Q(t) |Q(t)| \quad (11)$$

in which the constant  $K_f$  is calculated basing on the measured values of the initial flow conditions as follows:

$$K_f = K_{f0} = \frac{\Delta P_{f0}}{Q_0 |Q_0|} \quad (12)$$

The last term in the Eq. (10) is the unsteady term, depending on the rate of change of the discharge  $Q = VA$ . This term represents the effect of liquid inertia in the considered conduit



segment. For the steady-state flow this term is equal to 0, and then the above equation takes the form of the Bernoulli equation for the flow of a real liquid.

For simplification of notation let us introduce the following quantities:

- Static pressure difference between conduit sections 2-2 and 1-1 related to a reference level:

$$\Delta p = p_2 + \rho g z_2 - p_1 - \rho g z_1 \quad (13)$$

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

$$\Delta p_d(t) = K_d [Q(t)] , \text{ where } K_d = \frac{\alpha_2 \rho}{2 A_2^2} - \frac{\alpha_1 \rho}{2 A_1^2} \quad (14)$$

- Geometrical factor of the examined conduit segment of  $L$  length and  $A$  cross section area:

$$C = \int_0^L \frac{dx}{A(x)} \quad (15)$$

Then we get the differential equation (Eq. (10)) in the form:

$$\rho C \frac{dQ}{dt} = -\Delta p - \Delta p_d - \Delta P_f \quad (16)$$

After integrating this equation over the time interval  $(t_0, t_e)$ , in which the flow conditions change from initial to final stage, we obtain the discharge difference between these conditions. If we assume that we already know the discharge value in the final conditions ( $q_l$ ), i.e. after fully closing the shut-off device, we get the following formula for discharge in the initial conditions (before the water flow stopping was initiated):

$$Q_0 = \frac{1}{\rho C} \int_{t_0}^{t_f} (\Delta p(t) + \Delta p_d(t) + \Delta P_f(t)) dt + q_l \quad (17)$$

The discharge in the final conditions, if different from zero due to leakages through the shut-off device, has to be measured or assessed using a separate method.

The above integral formula reveals that in order to determine the discharge, the pressure drop  $\Delta P_f$  due to hydraulic loss in the examined conduit segment and the dynamic pressure difference  $\Delta p_d$  in the hydrometric cross sections of the conduit should be extracted from the measured static pressure difference  $\Delta p$ . The need for calculating these quantities, using their simplified dependence on the square of the flow rate (Eqs. 5, 6 and 8), unfavorably affects the accuracy of the measurement method.

#### 4.4 Versions of the pressure-time method

In practice, various versions (different variants) of the pressure-time method are used. The most important of them include – Fig. 20:

1. The classic version based on direct measurement of pressure difference between two hydrometric sections of the conduit using a pressure differential transducer.
2. The version making use of separate measurements of pressure variations in two hydrometric sections of the conduit.
3. The version based on measurement of pressure changes in one hydrometric section of the conduit and relating these changes to the pressure in the open liquid reservoir, to which the conduit is directly connected.

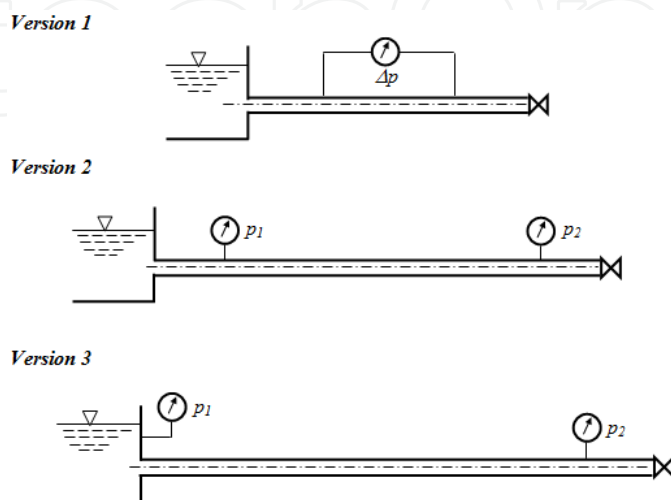


Fig. 20. Various versions of the pressure-time method.

The classic version based on the straight penstock measuring segment with constant diameter is mostly recommended in the standards. The results of measurements obtained using this version have the lowest uncertainty. Then, the version 3 belongs to the simplest and cheapest in using, that has significant importance from the economical point of view for small hydropower plants.

#### 4.5 Simplifying assumptions

When using the pressure-time method, one should be aware of differences between the real flow in conduits and its theoretical model taking into account certain simplifications. Along with the inaccuracy of the measuring devices used and numerical calculations applied, those simplifications can be the source of inaccuracy of the measurement method. The point is that the effect of those simplifications should not be too excessive and should not provoke significant errors in discharge measurement.

Basic simplifying assumptions of the pressure-time method refer to:

1. pressure independence of the liquid density and flow section area of the conduit,
2. negligible effect of residual (free) pressure oscillations in the conduit,
3. required constant pressure distribution in the measuring sections of the conduit,
4. method used for calculating friction loss in the measuring segment of the conduit,
5. method used for calculating dynamic pressure difference in cases of conduits with section area  $A$  changing with their longitudinal axis.

The effect of these simplifications is briefly discussed below.

**Ad.1.** The relative change of water density and the area of the penstock cross section in relation to the pressure increase  $\Delta p$  can be evaluated using the following formulas:

$$\frac{\Delta \rho}{\rho} = \frac{1}{E_w} \Delta p \quad (18)$$

$$\frac{\Delta A}{A} = \frac{D}{eE} \Delta p \quad (19)$$

where:  $\rho$  – liquid density,  $E_w$  – liquid bulk module,  $p$  – pressure,  $A$  – area of penstock cross-section,  $D$  – internal diameter of penstock,  $e$  – thickness of penstock wall,  $E$  – elasticity (Young) module of penstock material.

In the majority of cases of practical implementation of the pressure-time method to the penstocks of hydraulic machines, relative changes of the above quantities are extremely limited. For the water turbine flow systems with steel or concrete penstocks considered by the author of this chapter, the relative changes of those quantities did not exceed 0.1%.

$$\frac{\Delta \rho}{\rho} < 0.1\% \quad \frac{\Delta A}{A} < 0.1\% \quad (20)$$

**Remark:** The method can be used for cases in which the liquid density change and the pipeline wall deformation resulting from the pressure rise caused by stopping the liquid stream are negligibly small. These requirements are completely fulfilled for steel or concrete penstocks and for water considered as low-compressible fluid.

**Ad.2.** Despite the fact that the liquid density and the conduit diameter changes are negligibly small, their effect can be observed in the time-histories of the pressure changes in the conduit, mainly in the form of diminishing residual (free) pressure oscillations after full closure of the shut-off device. These oscillations around the equilibrium state do not affect the measured flow rate considerably, of course provided that they are properly considered. The way that can be used in this purpose is presented in the farther part of this chapter.

**Ad.3.** In large-dimension penstocks, keeping the pressure distribution constant is not physically possible. In order to obtain the best possible conditions, one should make sure that the locations of the measuring sections are properly selected, and the pressure measurements are performed using the manifolds that collect pressure from a several number of points uniformly distributed along the penstock perimeter. The IEC 60041 standard recommends measuring the static pressure difference between particular taps – it is important for the measured pressure differences not to exceed a certain limiting value, equal to 20% of the dynamic pressure.

**Ad.4.** A questionable issue in the method is calculating the pressure drop due to the friction between the measuring sections of the conduit – see Eq. (11). Since the nature of the water flow in large-dimension penstocks is strongly turbulent, then the use of these functions returns good results, especially for steady-state and for slowly changing unsteady flows. For such kind of flow, this is confirmed by the difference in the friction losses values (see Fig. 21) determined using the following formula:

$$\Delta P_f = f \frac{L}{D} \frac{V|V|}{2} \tag{21}$$

for cases when the friction coefficient  $f$  is considered as  $Re$ -dependent, calculated in accordance with the well-known empirical Colebrook-White formula (Cengel at al., 2006) and for cases when the friction coefficient  $f$  is constant  $f = f_0$ , determined for the initial flow conditions. The maximum relative difference between the losses calculated by these two ways does not exceed 2.5% for the conditions most frequently existed in hydro power plants. This value can be recognized as negligible when considering the small share of the friction losses in the pressure increment  $\Delta p$  - see below.

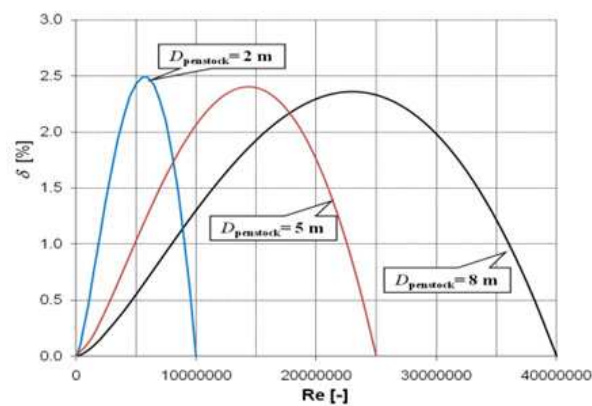


Fig. 21. Relative difference  $\delta$  between the friction losses in the pipeline segment determined using a variable friction factor  $f$  calculated from the Colebrook-White empirical formula and a constant coefficient  $f_0$  specified for the initial flow conditions (author’s own calculations).

Moreover, references (Brunone at al., 1991a; Bughazem at al., 2000) show that dissipation of mechanical energy during flow deceleration (taking place when the pressure-time method is applied) is slightly less than that obtained from the quasi-steady hypothesis, which is in opposite to accelerating flow where energy dissipation is much larger. Some of unsteady friction losses models in the closed conduits use these features (Brunone at al., 1991b. These models have been confirmed experimentally – there is a high conformity between experimental and numerical results of water hammer course (Adamkowski & Lewandowski, 2006).

In this context, it is of great importance for achieving good accuracy of the measurement performed using the considered method, that the contribution of the pressure difference attributed to hydraulic loss would be possibly the smallest and would not exceed a certain limit. This requirement can be written in the form of the following inequality, referring to the ratio of the pressure drop caused by the resistance in the initial conditions to the average value of the static pressure difference measured between the sections during stream stopping:

$$\left| \frac{\Delta P_{f0}}{\Delta p_m} \right| \leq \varepsilon_f \tag{22}$$

According to IEC 60041 standard, the value of  $\varepsilon_f$  is equal to 0.2 (20%) in cases of the classic version of the method (there is no difference of dynamic pressures between penstock measuring sections).

The consideration presented below shows that this requirement is sufficient when the discharge measurement accuracy is analyzed. For this purpose let us assume that discharge varies linearly during flow cut-off. This assumption is consistent with the conditions mostly occurring in the measurement practice. For such conditions, the  $\Delta P_{f0}$  value does not exceed 6.7% ( $33\% \cdot 20\% = \sim 6.7\%$ ) of the  $\Delta p_m$  value. Taking into account the results presented in Fig. 21 (2.5% inaccuracy of friction losses calculation using Eq. (11) and (12), the uncertainty of the discharge measurement coming from the calculation of the friction loss between the measuring sections of the conduit is very small, not higher than about 0.2% ( $6.7\% \cdot 2.5\% = \sim 0.17\%$ ).

**Remark 1:** Highly important for the realization of the requirement presented in the Eq. (22) is to select speed of closure of the shut-off device properly. The higher speed of the closure process causes the higher rise of the measured pressure difference change ( $\Delta p_m$ ), for the same pressure drop relating to the hydraulic loss in the initial conditions ( $\Delta P_{f0}$ ).

**Remark 2:** The theoretical description of the pressure-time method presented above is valid for both turbine and pump modes of operation. However, the IEC 60041 standard recommends using the method only in cases of turbine operation mode. Author's experiences indicate on the possibility to utilize the method also in cases of pumping operation mode. One of the necessary requirements in such cases is correct calculation of the hydraulic losses - pressure drop caused by the friction loss between the hydrometric cross sections of a pipeline. Typical calculation procedures, including the presented in the IEC 60041 and ASME PTC 18 standards, assume the hydraulic losses to be dependent on the square of the discharge value, as in the following equation:

$$\Delta P_f = K_f Q^2 \quad (23)$$

The hydraulic losses calculated in accordance with Eq. (23) do not depend on flow direction (both are always of the same sign) – as contrary to the Eq. (11). So, following this type of calculation may lead to the generation of additional error while determining the discharge value in the pressure-time method. It results from the fact that under some conditions, particularly in cases of pump-turbine tests, the significant temporary change of liquid flow direction takes place. The calculation procedure, based on Eq. (11) enables to account for actual flow direction and to increase measurement accuracy, particularly under pump mode operating conditions for which, in general, the temporary flow reversion during the pump shut-down required by the method occurs. The tests performed in the laboratory and *in situ* confirm the advisability of calculation of hydraulic losses from Eq. (11), particularly in cases when the pressure-time method is used to investigate hydraulic machinery characteristics under pumping regime (Adamkowski & Janicki, 2010).

**Ad.5.** Like for the friction loss calculations, a questionable issue is the dynamic pressure change  $\Delta p_d(t)$  calculations from the Eq. (14) in the cases of conduits with different hydrometric section areas. It is a well-known fact that the values of the Coriolis coefficients ( $\alpha_1$  and  $\alpha_2$ ) change in relation to the nature of the flow, in particular to the velocity distribution in the hydrometric sections of the conduit. For turbulent flows, these values are within the limits (1.04 - 1.1) (Cengel, 2006). Therefore, like in the case of the friction loss, assuring that the contribution of the dynamic pressure difference in the measured pressure difference is possibly the smallest and does not exceed certain limit is of high importance for

achieving good accuracy of the measurements performed using the pressure-time method. This requirement can be written in the form of the ratio of the dynamic pressure difference in the initial conditions ( $\Delta p_{d\max}$ ) to the average value of the static pressure difference measured between the measuring sections during stopping the liquid stream ( $\Delta p_m$ ):

$$\left| \frac{\Delta p_{d\max}}{\Delta p_m} \right| \leq \varepsilon_d \quad (24)$$

Obviously, to reduce the effect of the dynamic pressure difference on the result of the measurement, the proper selection of the hydrometric sections is highly important. They should be selected in such a way that their areas would least differ from each other. Moreover, it is recommended to tend to shorten the closure time of the shut-off device, and to keep the pressure distribution in the hydrometric sections not very disturbed, close to constant.

Besides simplifications discussed above, other main sources of inaccuracy of the considered discharge measurement method include the inaccuracy of the measuring devices used (Adamkowski & Janicki, 2007), the numerical calculations applied (Adamkowski & Janicki, 2010) and determination of the C factor in Eq. (17) (Adamkowski et al., 2009). Some selected issues are presented and discussed in the next part of this chapter.

## 4.6 Some chosen problems to be solved during applications of the pressure-time method

### 4.6.1 Determination of the upper integration limit of the pressure-time curve

Calculation of the initial value of discharge  $Q_0$  using the Eq. (17) requires to specify the time integration limits,  $t_0$  and  $t_f$ . These values should determine the time interval in which the flow is completely cut-off. Contrary to  $t_0$  time (lower limit of integration), the determination of  $t_f$  time (upper limit of integration) presents difficulties. Even precise synchronization of recording of the flow cut-off device run with measurement of the pressure rise does not ensure the exact determination of  $t_f$  time value. The reason for this is often the lack of the strict relation between the time moment at which the closing device movement is stopped and the time moment of flow cut-off finish - in some cases despite the termination of flow cut-off run, the closing device is still in motion, e.g. in result of elastic strain.

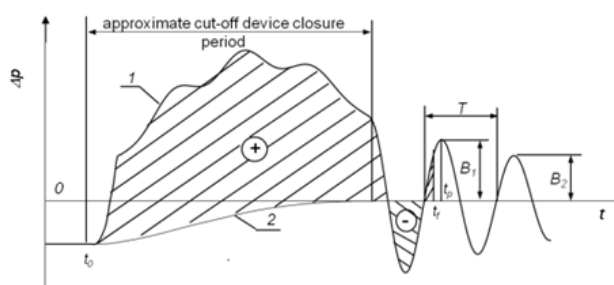


Fig. 22. Typical character of changes of pressure difference between the measuring penstock sections during flow stoppage and the notation applied.

Therefore, to determine the upper integration limit  $t_f$  the character of free pressure oscillations is presumed - Fig. 22. These oscillations remain in the penstock after the flow



cut-off, as a result of interaction between inertial effects and effects associated with liquid compressibility and deformability of the penstock shells. One of the procedures relating to the upper integration limit calculation in the pressure-time method is given in the IEC 60041 standard. However, it includes mathematical inaccuracy – the author of this chapter has proved that it does not ensure to set a zero-value integral of free pressure difference oscillations that intent to eliminate their influence on the discharge measurement (Adamkowski & Kwapisz, 2000; Adamkowski & Janicki, 2010). The consideration regarding the relevant explanation and the procedure improvement are presented below.

Let us assume that free pressure oscillations after the termination of flow cut-off may be described by the following function (Fig. 23):

$$\Delta p(t) = B_0 e^{-ht} \cos(\omega t) \quad (25)$$

with  $\omega = 2\pi/T$  denoting the circumferential wave frequency,  $h = (1/T) \ln(B_0/B_1)$  – oscillation damping coefficient (reciprocal of the relaxation time),  $\ln(B_0/B_1)$  – logarithmic damping decrement,  $T$  – pressure wave period.

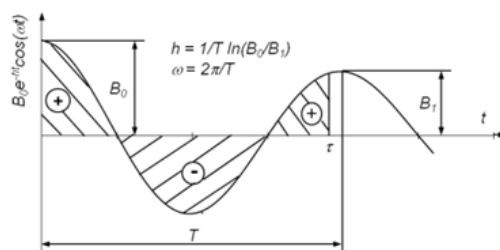


Fig. 23. Free pressure oscillation run including the notation applied.

In order to avoid the influence of diminished free pressure oscillations on the discharge value to be determined, the time point  $\tau$ , fulfilling the condition

$$\int_0^{\tau} B_0 e^{-ht} \cos(\omega t) dt = 0 \quad (26)$$

is sought for. Eq. (26) represents the condition of equal total fields (areas) defined by the diminished pressure wave curve below and over the time axis – Fig. 26.

Basing on the analysis performed, it has been stated that the procedure of determining the  $\tau$  time, as presented in the IEC 60041 standard does not lead to a strict solution of Eq. (26). It can be proved that this procedure follows from the solution of an equation based on the indefinite integral of Eq. (26) which can be determined analytically. By solving the following equation:

$$\int B_0 e^{-ht} \cos(\omega t) dt = B_0 \frac{e^{-ht}}{h^2 + \omega^2} [-h \cos(\omega t) + \omega \sin(\omega t)] = 0 \quad (27)$$

in respect to time  $t$ , one derives an analytical expression which is consistent with the presented in the IEC 60041 standard and used to determine the end of the integration interval. The precise (strict) solution should be based on the definite integral of Eq. (26) which can be written down in the following form:

$$\int_0^{\tau} B_o e^{-ht} \cos(\omega t) dt = \frac{B_o}{h^2 + \omega^2} \left\{ e^{-h\tau} [-h \cos(\omega \tau) + \omega \sin(\omega \tau)] + h \right\} = 0 \quad (28)$$

Equation (28) cannot be solved analytically. By comparing equations (27) and (28) it can be seen that the term:

$$\text{Eq. (28)} - \text{Eq. (27)} = B_o h / (\omega^2 + h^2) \quad (29)$$

has not been taken into account by the IEC 60041 standard procedure.

From these considerations it is evident that one of the possibilities to eliminate the influence of free pressure oscillations on the calculated discharge is to subtract the value  $B_o h / (\omega^2 + h^2)$  from the integral value calculated from the recorded pressure difference diagram as proposed in the IEC 60041 standard. The value resulting from Eq. (29) can be easily calculated basing on the recorded pressure-time diagram.

Another approach aimed at eliminating the effect of free pressure oscillations is the numerical determination of solution of the integral given by Eq. (26) (Adamkowski & Kwapisz, 2000).

The influence of free pressure oscillations generated in the pipeline after the flow cut-off on the discharge measurement realized by means of the pressure-time method increases as the free oscillation amplitude increases. It appears from the author's experience that in some cases it may achieve 0.5% of determined discharge.

#### 4.6.2 The influence of a curved penstock application on discharge measurement

Following the classical approach (version 1), the pressure-time method applicability is limited to straight cylindrical pipelines with constant diameters. However, the IEC 60041 standard does not exclude application of this method to more complex geometries, i.e. curved penstock (with an elbow). It is obvious that a curved pipeline causes deformation of the uniform velocity field in its cross-sections, which subsequently causes aggravation of the accuracy of the pressure-time method flow rate measurement results – Fig. 24. So, the influence of a curved penstock application on discharge measurements by means of the considered method should be taken into account. The author of this chapter and his co-workers have developed the special calculation procedure for solving that problem (Adamkowski at al., 2009). The procedure is based on the CFD (*Computational Fluid Dynamic*) simulation – Fig. 25. It allows calculating the equivalent value of the geometry factor  $C$  (see Eq. (15)) for a measuring penstock segment with an elbow (or elbows). The value can improve the discharge measurement results of the standard pressure-time method without curved penstock correction. As an example, the systematic uncertainty caused by neglecting the effect of the two elbows on measured discharge values has been estimated – Fig. 26 (Adamkowski at al., 2009). In the considered case, the average value of the quantity  $\Delta f = 0.45\%$  was taken to correct the discharge values following from the calculation carried out for the  $C$  factor obtained only from the geometry of measuring penstock segment.

Similar approach, based on the CFD simulation, is needed for determining the value of  $C$  factor for whole penstock while the pressure time method in the version 3 is used. The author of this chapter strives to develop a special procedure for this purpose. It is assumed

that this procedure should allow for applying the version 3 of pressure-time method in penstocks shorter than it follows from the current requirements of the IEC 60041 standard – in addition to ensure increasing measurement accuracy of this method.

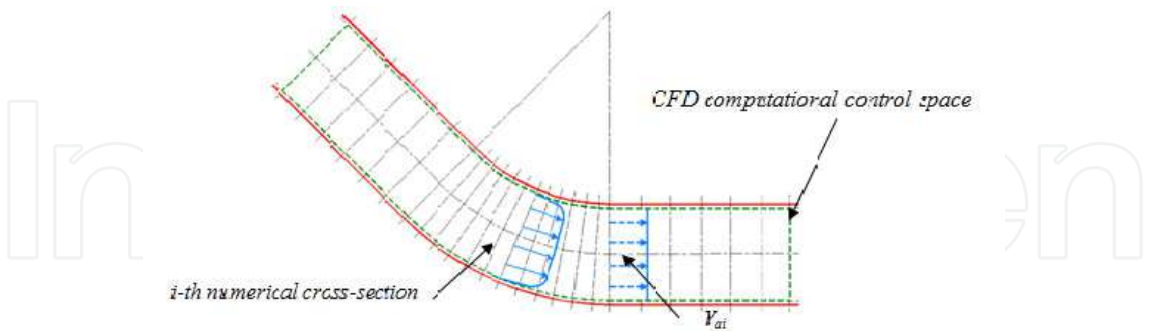


Fig. 24. A penstock elbow with marked computational space.

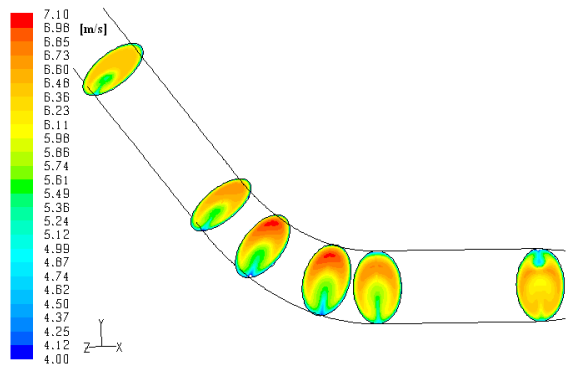


Fig. 25. The velocity magnitude distributions in the penstock cross-sections calculated for discharge of  $Q = 200 \text{ m}^3/\text{s}$  (Penstock diameter 6.5 m).

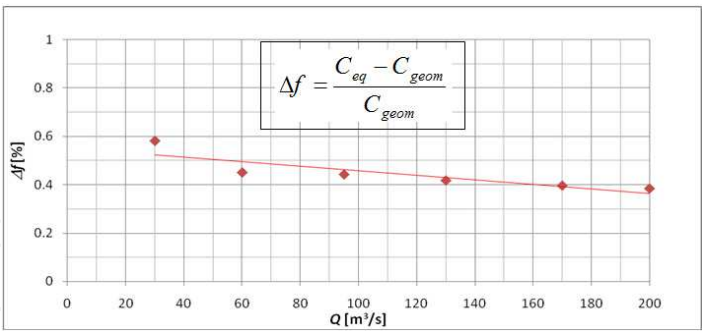


Fig. 26. The values of  $\Delta f$  deviation factor  $C$  determined for the assumed discharge values for the considered case of measuring penstock segment with two elbows ( $C_{geom}$  is the value of  $C$  factor determined only from the geometry of the measuring penstock segment and  $C_{eq}$  is the equivalent value of  $C$  factor determined with correction obtained using the proposed procedure).

4.6.3 Using the pressure-time method based on special instrumentation installed inside penstocks

Discharge measurement using the pressure-time method typically requires mounting instrumentation on the outside of the penstock. In the case of a hydropower plant where the

penstock is embedded in concrete traditional way for using that method is not possible. Therefore, an approach that involved installing discharge measurement instrumentation inside the penstock has been recently developed (Adamkowski at al., 2006b, 2008; Adamkowski & Janicki, 2008). One of the first applications of such kind of techniques is presented below.

In the considered case, the discharge was measured using the pressure-time method in the version based on separate pressure difference measurements in two hydrometric cross sections of the penstock, 1-1 and 2-2 – Fig 27.

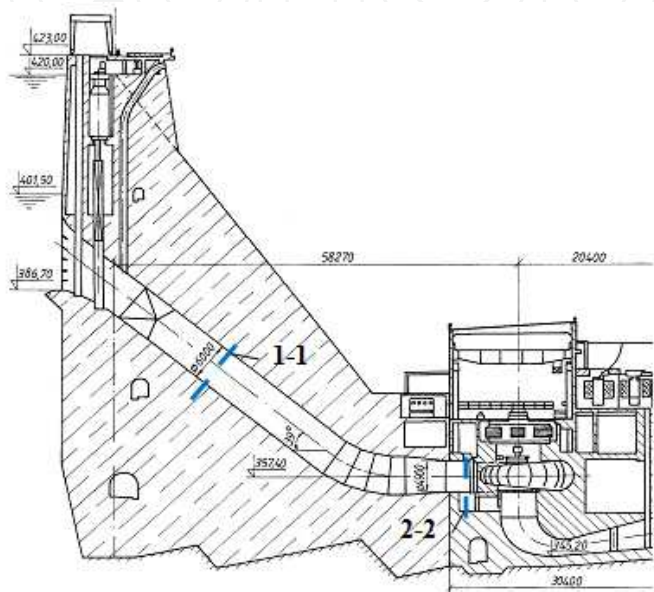


Fig. 27. A scheme of the flow system in one of the Polish hydropower plants with marked cross-sections used for discharge measurement.

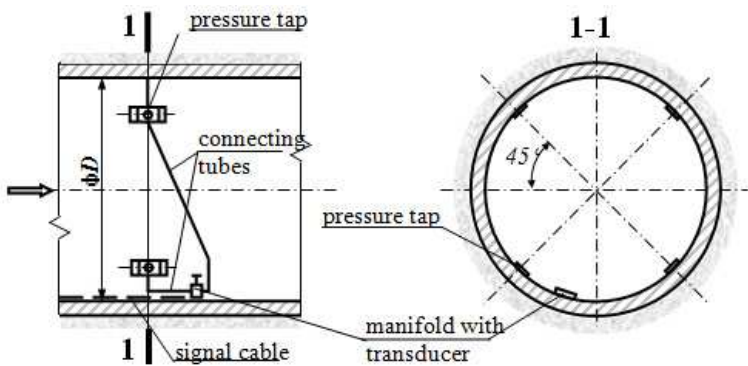


Fig. 28. Distribution of pressure reception holes (taps) in measuring section 1-1 and their connection to the hermetic manifold with absolute pressure transducer installed inside.

In each of those sections, 4 pressure taps (or pressure reception holes) were prepared and connected using small tubes to the manifold and pressure transducer. A typical manifold was used in the lower penstock section 2-2. There was possibility to prepare the whole system of collecting and measuring pressure from the taps, having the access from outside.

Since there was no access from outside to the upper penstock section 1-1, a special internal installation was prepared for pressure reception and measurement – see Fig. 28, 29 and 30. The Fig. 29 shows a flat bar with the specially drilled hole for the pressure reception. The hole diameter was equal to 3 mm. The flat bar was welded to the penstock shell, respectively to the flow direction. Four pressure reception holes were connected, using copper tubes of 10 mm diameter, to the manifold with absolute pressure transducer of precision class 0.1 mounted hermetically inside it – Fig. 30.

It is worth stressing that preparing the pressure measuring system inside a penstock of 6 meters in diameter and inclined by an angle of 40 degrees was an extremely difficult task.

Figure 31 shows: the time-histories of the static pressures measured in the selected and prepared sections 1-1 and 2-2, the static pressure difference determined from them, and the discharge calculated according to the pressure-time method.

After preparing and mounting the entire instrumentation inside the penstock, filling this with water and full deaeration was of high importance task. On the contrary to easy way of the deaeration performed in typical, external installation of pressure measurement, in the presented case for the 1-1 hydrometric section a special procedure had to be applied (description of this procedure goes beyond the scope of this chapter).



Fig. 29. View of the plate with a pressure reception hole.

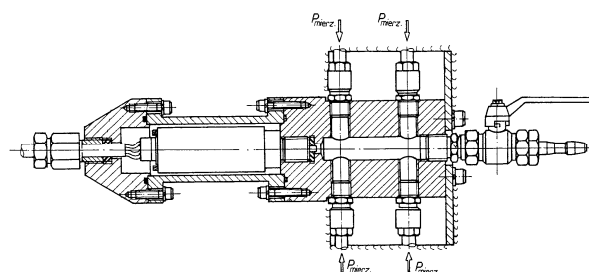


Fig. 30. Manifold with absolute pressure transducer hermetically mounted (own application).



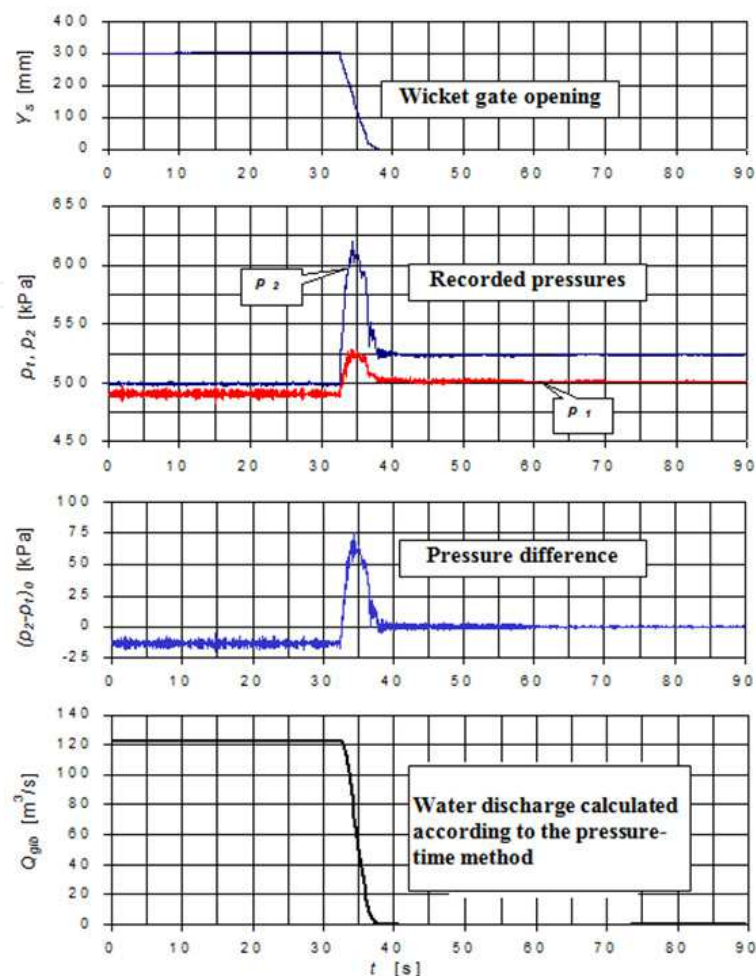


Fig. 31. Pressure changes measured in the measuring sections of the classical turbine penstock, and the discharge determined from them (own application).

#### 4.6.4 Measurement of leakage flow through closed hydraulic turbine wicket gates

As it was mentioned above, applying the pressure-time method for discharge measurement requires determination of the rate of leak flow through gaps of closed shut-off devices, for instance wicket gates of hydraulic machines. The technique mostly used for this purpose is based on time-record of water level decrease in cylindrical segments of a penstock or surge tanks during turbine standstill. This technique allows to determine the leakage rate through closed devices in cases where the inflow due to leakage past closed intake gates has to be measured or estimated using an additional, separate method. The separate measurement of the rate of such inflow is rather complicated and usually burdened with significant uncertainty. Therefore, the extension of the aforementioned technique aimed at eliminating separate measurement of leakage through closed intake gates has been developed and presented in (Adamkowski & Janicki, 2009). The proposed technique is based on simultaneous measurement of pressure on both sides of a closed guide vane apparatus and on applying the square root dependence between determined leakage flow rate and recorded pressure difference between the measuring points. Short description of this technique is presented below.



According to the principle of mass conservation it can be written (see Fig. 32):

$$q - \frac{dV}{dt} = q_l \quad (30)$$

where  $q$  means the flow rate of leakage through the turbine intake gates closure (flow into the control water volume  $V$ ),  $q_l$  – flow rate of leakage through the closed turbine guide vanes and  $dV/dt$  – time derivative of water volume inside the penstock segment.

The derivative  $dV/dt$  can be calculated numerically according to formula:

$$\frac{\Delta V}{\Delta t} = \frac{A}{\sin \beta} \frac{\Delta z}{\Delta t} = \frac{A}{\rho g \sin \beta} \frac{\Delta p_t}{\Delta t} \quad (31)$$

where  $A$  is the area of constant pipeline cross-section,  $z$  – water level inside the penstock,  $p_t$  – pressure before the closed shut-off device, for instance, in the turbine spiral case when guide vane is a shut-off device,  $\rho$  – water density,  $g$  – acceleration of gravity and  $\beta$  – slope angle of penstock axis.

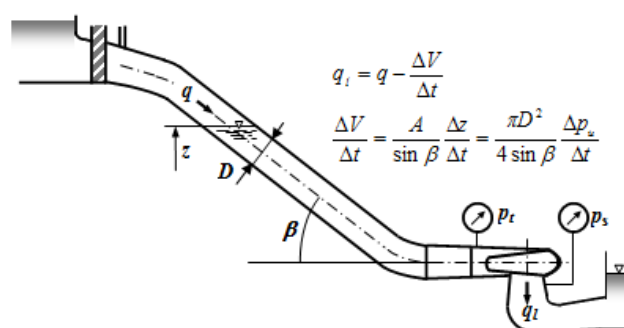


Fig. 32. Schematic illustration for explaining the measurement technique of leakage flow rate through the closed turbine wicket gates or other shut-off devices. ( $q_l$  – leakage flow rate through the closed guide vanes,  $q$  – rate of outflow through the intake gate,  $V$  – volume of water in a penstock,  $t$  – time).

On the basis of fluid dynamics, the leakage flow rate  $q_l$  is approximately proportional to the square root of the pressure difference between both sides of the shut-off device and may be expressed as follows:

$$q_l = a(p_t - p_s)^{0.5} \quad (32)$$

The proportionality coefficient  $a$  can be determined on the basis of recorded pressures in time  $p_t(t)$  i  $p_s(t)$  – Fig. 33 – and the calculations of time derivative of water volume change inside the pipe  $\Delta V/\Delta t$  in accordance with Eq. (31). (The pressures  $p_t$  and  $p_s$  have to be referred to the same level.) The way of determination of leakage flow rates  $q_l$  and  $q$  is presented graphically in Fig. 34. The results obtained from the test and calculation are presented in the coordinate system of  $x = (p_t - p_s)^{0.5}$  and  $y = \Delta V/\Delta t$ . Then, they are approximated by means of the least square method using linear function  $y = ax + c$ , where constants  $a$  i  $c$  stand for, respectively, the value of coefficient  $a$  in Eq. (32) and the rate of the outflow through the intake gate,  $q = -c$ .

Applying Eq. (32) will enable to recalculate the leakage flow rate  $q_l$  through the closed devices for the conditions existing after the turbine shutdown during discharge measurement test by means of the pressure-time method. (Also this technique enables to determine value of leakage flow rate during the turbine standstill for the pressure difference equal to the gross head.)

Two considered cases concerning the measurement of leakage flow rate through the hydraulic turbines are presented in (Adamkowski & Janicki, 2009).

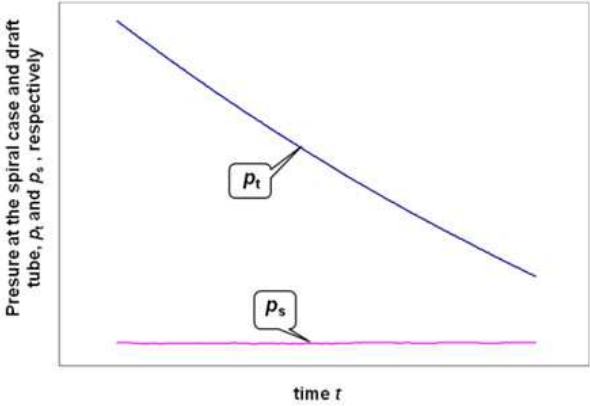


Fig. 33. Example of pressure variations in a spiral case and a draft tube recorded during leakage test (own application (Adamkowski & Janicki, 2009)).

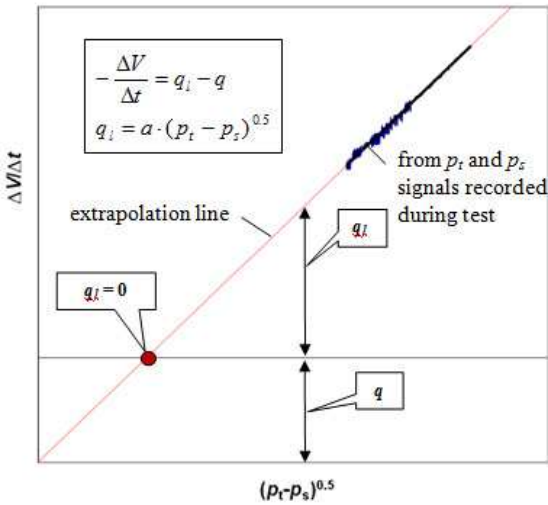


Fig. 34. Example of the results obtained from the leakage test conducted in a Francis turbine system - rate in water volume  $\Delta V$  change in penstock control area was determined as a square root function of pressure difference between two sides of the turbine guide vanes,  $p_t$  i  $p_s$ . (own application (Adamkowski & Janicki, 2009)).

## 5. Conclusions

1. Standard measuring devices, such as constriction flow meters (orifice plates, flow nozzle or Venturi tube), calibrated pipe elbows, electromagnetic and ultrasonic flow meters can be used for flow rate measurements in conduits of small diameters, for instance up to 1 m. Such kind of devices are mounted in a properly prepared measuring

- segment of the conduit and can be used for continuous discharge measurement as an important part of monitoring of hydraulic systems.
2. Large-scale discharge measurements in hydropower systems are the most complicated, costly ineffective and having higher level of uncertainty with comparison to measurement of other quantities (head and power) needed to determine hydraulic performance of water turbines. The correct application of discharge measurement techniques in large-scale objects is usually a major challenge, despite recent immense progress in those techniques.
  3. Among a few primary methods for absolute discharge measurements in hydropower systems (velocity-area method, pressure-time method, tracer method, ultrasonic method and volumetric method), the most attractive from practical point of view is the velocity-area method and the pressure-time method. The tracer method is less popular, mainly, due to requirement of a very long measuring segment of flow conduits and special, additional conditions facilitating the mixing process of the introduced marker. The volumetric method has very limited area of application - generally it can be used in hydropower plants equipped with artificial reservoirs, particularly in pumped-storage plants. The ultrasonic method is still the object of numerous research activities oriented on its improvement and has still not reached proper acceptance among the most specialists.
  4. The velocity-area (propeller current meter method, for instance) is specially recommended and available for discharge measurement in low and very low head water power plants with short intakes of turbines, although further progress in acoustic scintillation techniques may change this situation.
  5. The pressure-time method is a very attractive one for discharge measurements in the hydropower plants equipped with penstocks longer than 15-20 m. Recently, 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 earlier when for its outdated versions the optical techniques to record pressure changes combined with the manual graphical integration was used.
  6. The recent progress and improvement in discharge measurements using the pressure-time method refers, mainly, to: (1) successful development of the special instrumentation installed inside penstocks in the frequent practical cases where there is no access to the penstock from outside, (2) changes of the discharge calculation procedure based on the recorded pressure-time diagram, and (3) development of the original way for measuring of leakage flow through the closed turbine guide vanes.
  7. The special numerical procedure for evaluating the influence of an elbow (or elbows) on discharge values measured using the pressure-time method was recently developed. The procedure, based on the CFD simulation, allows to determine the equivalent value of the geometry factor for a measuring penstock segment with elbows. It is recommended to use for correction of discharge measurement results for cases of penstocks with elbows.
  8. It is expected to use the pressure-time method in the simplified version – the version 3 based on measurement of pressure changes in one chosen hydrometric section of the penstock and relating these changes to pressure in the water reservoir supplying the penstock directly. Such kind of an application is very important for small hydropower

plants concerning economical issues. It seems that the special procedure based on the CFD simulation should allow to use this version of pressure-time method in penstocks shorter than it follows from the IEC 60041 standard requirements, and, in addition, to increase accuracy of discharge measurement in such hydraulic systems.

9. Not all theoretical issues of the pressure-time method have been solved comprehensively. Ones of those unsolved issues concern calculation of the friction loss during the unsteady flow of liquid in closed conduits and calculation of dynamic pressure difference between the measuring conduit sections. The method adopted for calculating these quantities, justified for the steady-state flows, should be verified in unsteady conditions.
10. To achieve the expected accuracy of the measurement, the selection of conditions in which the pressure-time method is used, along with the measuring devices applied, should be based on the analysis of the measurement uncertainty, recommendations given in relevant standards, as well as personal experiences gained.

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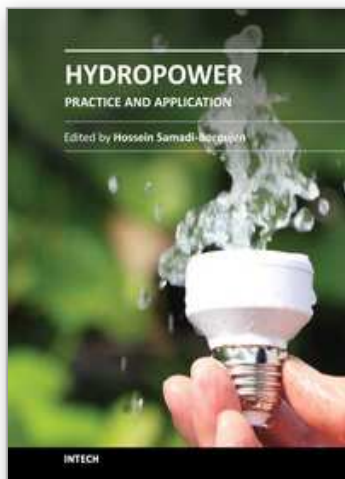
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Hydroelectric energy is the most widely used form of renewable energy, accounting for 16 percent of global electricity consumption. This book is primarily based on theoretical and applied results obtained by the authors during a long time of practice devoted to problems in the design and operation of a significant number of hydroelectric power plants in different countries. It was preferred to edit this book with the intention that it may partly serve as a supplementary textbook for students on hydropower plants. The subjects being mentioned comprise all the main components of a hydro power plant, from the upstream end, with the basin for water intake, to the downstream end of the water flow outlet.

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