SMALL HYDRO ACTION
FOR PROMOTION OF EFFICIENT SOLUTIONS

R&D Actors Network Meeting

The Szewalski Institute of Fluid-Flow Machinery
Gdansk (Poland), September 10-11th, 2009

PROCEEDINGS

The Szewalski Institute of Fluid-Flow Machinery
of the Polish Academy of Sciences

Gdansk, August 2010

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Preface

The present volume brings written contributions submitted to the Organising Committee of the SHP Research & Development Actors Network Meeting held in the premises of the Szewalski Institute of Fluid-Flow Machinery of the Polish Academy of Sciences on September 10th and 11th, 2009. The purpose of this event was a debate on the SHP oriented research & development trends. The event was organised within the work package 2 (WP2) of the SHAPES (*Small Hydro Action for Promotion of Efficient Solutions*) project, funded by the European Commission as a part of the specific research and technological development programme „Integrating and Strengthening the European Research Area (2002-2006), Sustainable Energy Systems" (6th EU Framework Programme). The work package was co-ordinated by the MHylab Foundation located in Montcherand (Switzerland) whereas the *European Small Hydropower Association* (ESHA) co-ordinated whole the project.

The event took the form of a series of debates on the following groups of problems as identified by the Work Package Co-ordinator.

1. **HYDROLOGY**
   covering: Maps, hydrology and residual flow, potential identification
2. **GENERAL DESIGN & CIVIL ENGINEERING WORKS**
   covering: Multipurpose projects, weirs & water storage
   desilter, water intakes & trashracks, penstocks
3. **ENVIRONMENTAL ISSUES**
   covering: Environmental integration, bioengineering, fish passes,
   waterways, environmental Impact Assessments
4. **PERFORMANCE & TECHNICAL STATE ASSESSMENT TECHNIQUES, OVERHAUL AND REHABILITATION WORKS**
   covering: Performance, technical state and residual life assessment techniques,
   methods and equipment for construction & maintenance,
   repair, overhaul and rehabilitation of SHP plants
5. **ELECTROMECHANICAL EQUIPMENT**
   covering: Turbines and integrated hydraulic units
   Possible synergies with wind power and marine technologies
6. **ELECTRICAL EQUIPMENT, CONTROL & MONITORING**
   covering: Electrical equipment, control & monitoring

Following the adopted formula, each debate was to be introduced by a keynote address delivered by a specialist in the relevant field. In addition to the keynote addresses (state-of-the art surveys) we had also one case study (Downar & al) and three discussion contributions (Popa and Grahl Madsen). All contributions were submitted to the Organising Committee in form of MS Power Point presentations. The Organising Committee has copied them to the flash disks handed to the Event Participants at the end of the Meeting. The list of all 14 presentations available at the flash disks is to be found at the end of this document.

Most of contributions was followed by discussion which by means of a dictaphone. The report on this discussion is to be found in the Final Report of the Network Meeting together with a subjective summarisation of all the contributions[1].

Some speakers have followed our suggestion and submitted their presentations in form of full-length papers. Now these papers are being made available. There are 6 papers altogether to be found in this volume. All of them are being published at full responsibility of the authors as no editorial correction has been conducted except some reformatting of the text and numbering of pages.

Two papers by Prof. A.Adamkowski bring a survey on his experience in the field of *Performance & technical state assessment techniques of SHP mechanical equipment*.

The paper of our colleagues from the Institute of Power Engineering is a case study showing capabilities offered by contemporary technology in the field of monitoring and control of small hydropower plants.

The paper by Dr Nino Frosio is a guide on his excellent lecture *Overhaul and rehabilitation of the civil works*. It is highly recommended to study it together with his MS Power Point presentation.

Two last papers are discussion contributions by Prof. Mads Grahl Madsen. Both of them have sparked really vigorous discussion during the Event.

The Organising Committee takes herewith the opportunity to express the deepest appreciation of the effort by the authors and speakers having contributed to the Network Meeting. We are also highly indebted to all discussers as an open and fair debate was surely the essential value of the Event.

With this document we hope having contributed to stimulating further exchange of opinions and setting new intriguing questions in the field of technology that is still open for research and creative ingenuity

For the Network Meeting Organising Committee

Dr Janusz Steller

Chairman

Gdansk, August 2010

[1] Steller J., Kaniecki M.: *Small Hydro Research & Development Actors Network Meeting - Final Report*. IMP PAN Rep. 437/2010

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shapes

SMALL HYDRO ACTION
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R&D Actors Network Meeting

The Szewalski Institute of Fluid-Flow Machinery
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Essential methods of SHP efficiency testing

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1. INTRODUCTION AND GENERAL REMARKS

The turbine efficiency (net efficiency) is determined from the following formula:

$$\eta_t = P_m/(E\rho Q) = P_m/(\rho g H Q) \qquad (1)$$

while the efficiency of the entire hydro-unit (gross efficiency) is determined from the formula:

$$\eta_b = P_e/(\rho g H_b Q) \qquad (2)$$

where P_e is mechanical power on the turbine shaft, P_e is active electric power, measured at generator terminals, g is gravity acceleration (its current value should be determined for the location of the power plant – the latitude and position above sea level), ρ is water density, to be determined by measurement or from the table included to the IEC 41 standard for the absolute pressure in the machine flow system and water temperature during the measurement, H_b is the gross head; $H_b = z_g - z_d$ (z_g - upper water level ordinate, z_d – lower water level ordinate).

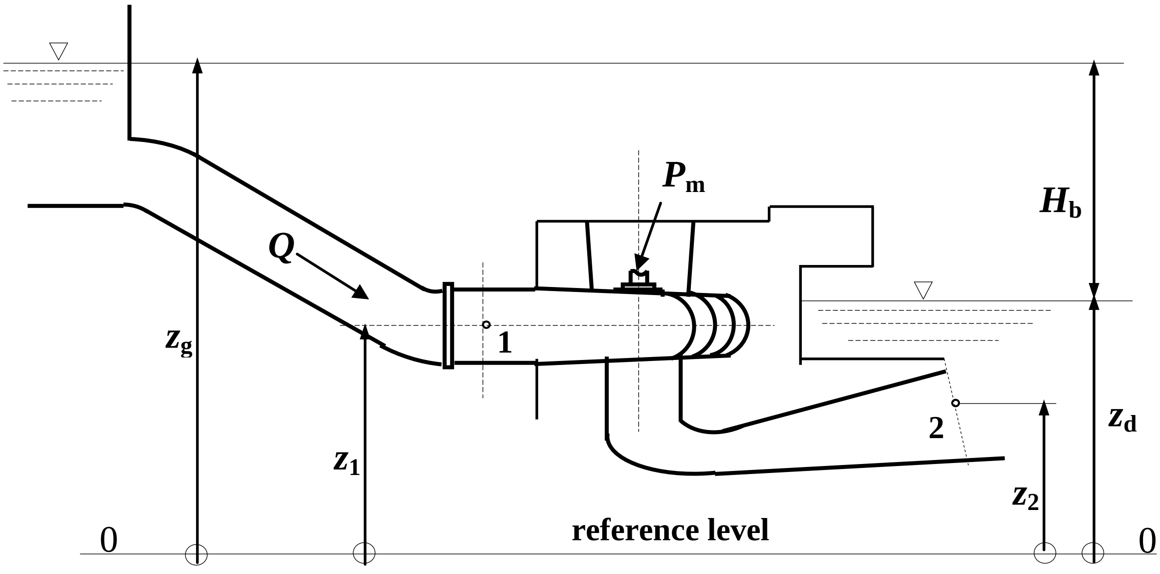

Fig. 1 Schematic of the flow section through the water turbine, with marked basic performance test quantities
***Q* – flow rate, H_b – power plant head (gross), P_m – mechanical power (on turbine shaft)**

Except for the thermodynamic metod, determining of the turbine and hydraulic unit efficiency requires measurement of discharge Q, mechanical power (at the shaft) P_m, electrical power P_e as well as net and gross head (or specific hydraulic energy).

The most complex and least accurate measurement is that of discharge. Additionally in low-head power plants and in particular very low head power plant accurate measurement of head is also problematic. Selected problems of discharge measurement in small hydro power plants are presented in the further part of this paper.

1.1. Short description of flow measurement methods

Measuring water flow rate in conduits with small diameters, for instance up to do 1 m, is not a difficult task. Typical, standard measuring devices, such as construction flow meters (measuring orifice plates, nozzle or Venturi tube) – Fig 2, electromagnetic flow meters - Fig. 3, or calibrated pipe bends (elbows) - Fig. 4 are used in such conduits. These devices are usually mounted in a properly prepared measuring segment of the conduit.

The situation is different when the water flow rate is to be measured in large-dimension conduits, having the diameter of an order of several and more meters. Measurements flow rate in these conduits, frequently used in waterpower engineering, are very difficult and expensive. At present it is expected to measure flow rate within +- 1% systematic uncertainty.

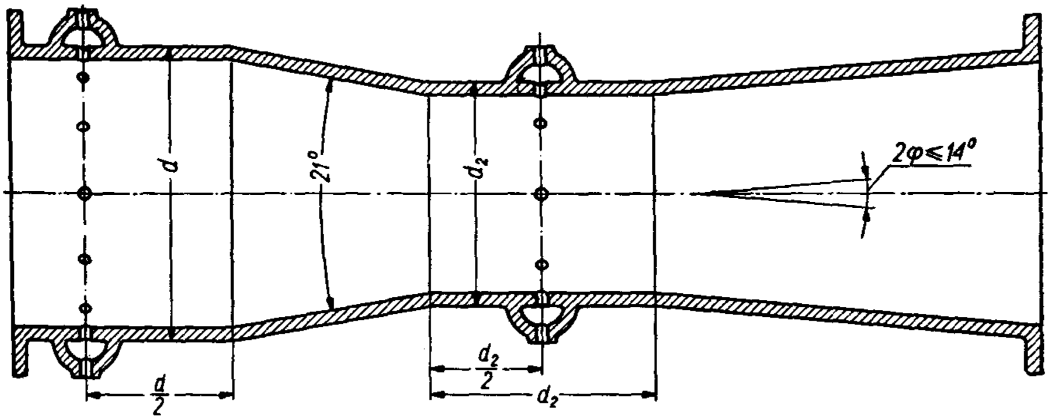

Fig. 2 Standard conical-type *Venturi tube* .

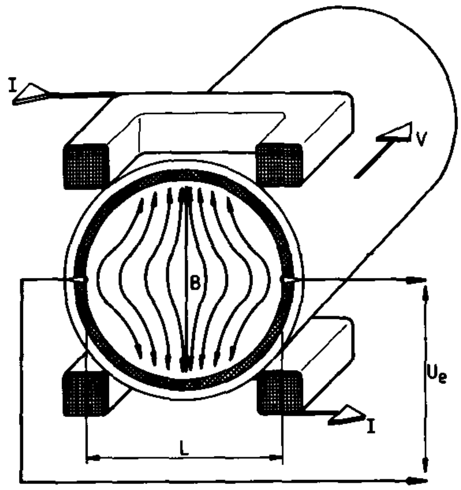

Fig. 3 Electromagnetic flow meters (using phenomenon of inducting electromagnetic force caused by flow of conducting fluid – Faraday low)

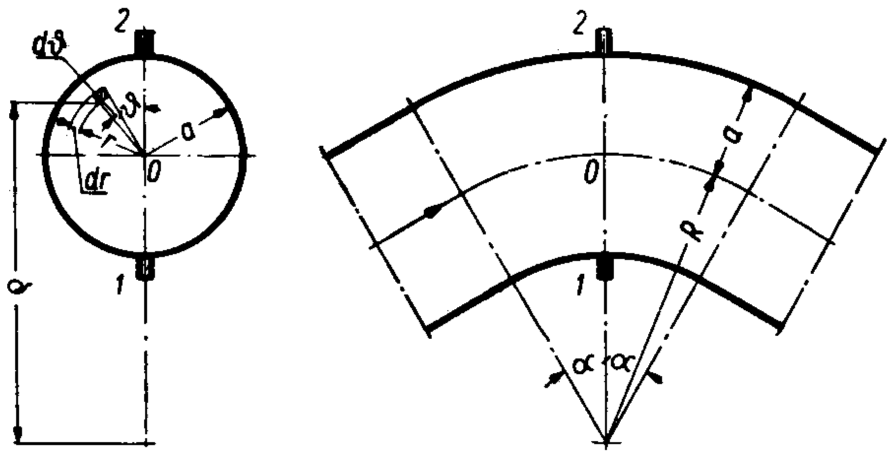

Fig. 4 Calibrated pipe elbows
(measuring pressure difference between outer and inner walls of a bend caused by centrifugal force).

1.2. Review of methods for flow rate measurement in large-dimension conduits

There are only a few primary methods of the flow rate measurement in water power plants:

- The **velocity-area method** utilizing the distribution of local velocities, measured using hydrometric current meters (Fig. 5) - in cases of large penstock diameters - or impact pressure velocity meters (Pitot tubes or Prandtl tubes, Fig. 6) - for smaller diameters and clean water. The volumetric flow rate is determined by integrating this distribution over the entire area of the measuring section.

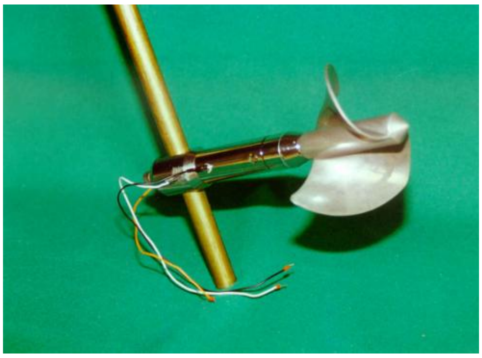

Fig. 5 Hydrometric current meter

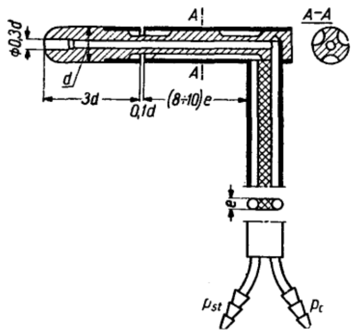

Fig. 6 Prandtl measuring tube

- The **pressure-time method** (water hammer or Gibson method) – based on measuring the time-history of pressure difference changes between two hydrometric sections of the conduit during full stoppage of the liquid stream with the aid of a cut-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 during stoppage of the stream of liquid.

- The **tracer method** consisting in measurements of the passing time, or concentration, of the radioactive or non-radioactive substance (salt, for instance) between two sections of the penstock. The method requires long pipes and conditions for good mixing of the marker.

- The **ultrasonic method** – based on vector summation of the 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.

Three first methods on the above list belong to the group of traditional (classic) methods, while the fourth method, the ultrasonic method, is relatively young and is recently the object of numerous research activities oriented on its improvement. This method has not reached yet proper acceptance among the specialists. The international standard IEC 60041 suggests conditional use of this method, i.e. in case of explicit agreement of all contracting parties. Its basic advantage is the possibility of use for continuous flow rate measurement. Other methods do not reveal this advantage.

Among classic methods the least popular is the tracer method. 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 basic methods of flow rate measurement in turbine penstocks include: the local velocity distribution method and the water hammer method (Gibson method). It is also noteworthy that the local velocity distribution method, mainly making use of hydrometric current meters and most frequently used in waterpower engineering in the past, is nowadays being replaced by the Gibson method in the hydropower plants equipped with penstock longer then 10-20 m. The reason is much lower cost of preparation and performance of the measurement based on the Gibson method, and the use of computer techniques in recent ten or twenty years, which facilitate the measurements and provide opportunities for higher accuracy of the results obtained using this method.

Relative (index) methods, such as: the Winter-Kennedy method and the methods utilizing non-standardized pressure difference devices, non-standardized overflows or reducers, some simple variants of the acoustic method or local velocity measurement with aid of a single current meter, can be used for determining the relative value of the flow rate, or even the absolute (physical) value, provided that calibration has been done on site by comparing with the results of measurements using the absolute method.

2. METHOD OF FLOW RATE MEASUREMENT USING HYDROMETRIC CURRENT METERS (VELOCITY-AREA METHOD)

The current meter method, frequently used in efficiency tests of the small water turbines, consists in:

- the use of propeller hydrometric current meters located at certain points of a correctly selected hydrometric section in the open channel or closed section in order to determine velocity field components in this section,
- flow rate calculation based on proper integration of the velocity field over the area of the measuring section.

The water flow velocity components are measured based on the current meter rotor revolutions counted in a given time period, and the experimentally determined relation between the current meter rotor revolutions and flow velocity. The flow rate is obtained by integrating the results of simultaneous local velocity measurements over the measuring section area – Fig. 7. In general notation it can be written as follows:

$$Q = \iint_A V_z(x, y)\,dxdy \cong \sum_i V_{zi} \Delta x_i \Delta y_i$$

where V_z is local velocity component in z-axis direction of the channel or conduit, x and y –axes perpendicular to *z-axis*, A – area of the measuring (hydrometric) section perpendicular to z-axis.

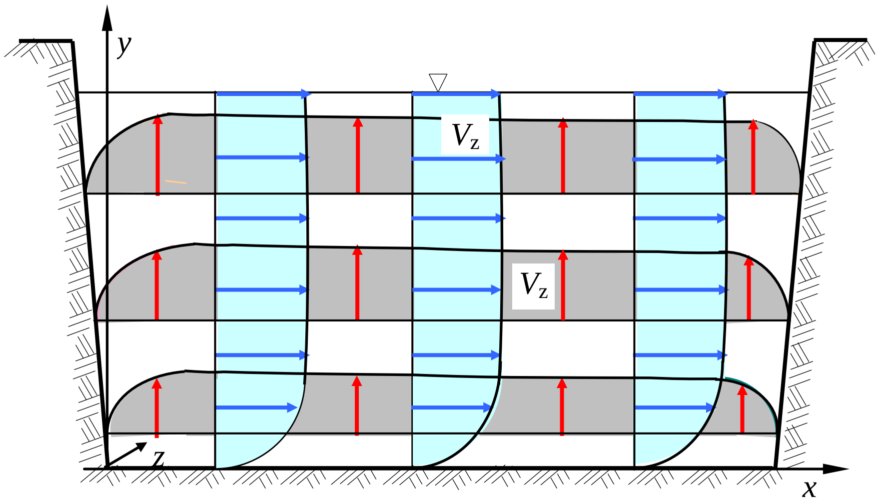

Fig. 7 Water velocity distribution in the section of open (trapezoidal) channel

The discussed method of flow rate measurement bases on an assumption that the real velocity distribution is determined by velocity components measured using current meters, and in the boundary layer (the vicinity of the walls of fixed objects) is well approximated by the distributions given by well known formulas. The adopted extrapolation formula for velocity distribution in the boundary layer of an open channel has the form:

$$V_\mathrm{x} = V_\mathrm{a}\ (x/a)^{1/\mathrm{m}}$$

where:

> V_x is the velocity at a distance x from the nearest wall, V_a is the velocity at the extreme measuring point, a is the distance from the wall to the nearest current meter jest, m is boundary layer development coefficient, depending on the wall roughness and flow conditions, m = 2-14.

This method can be used in each properly selected measuring (hydrometric) section situated in :

- a closed conduit or penstock,
- a water intake structure (water lock),
- an upstream or downstream open channel.

The development in measuring techniques employing current meters is mainly connected with the use of a computer, instead of manual planimetring, for integrating the determined velocity field, and for counting rotor pulses. Those two factors, i.e. the computer-aided calculation of the flow rate value via integrating the velocity field determined by hydrometric current meters in the measuring section, and the computer-aided counting of flow meter pulses, act towards increased accuracy of the measurement, and decrease of its laboriousness.

Discharge measurement in low-head installations is 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.8) is considered the optimum one. On the one hand side, such a location enables mounting current-meters on a traversing frame resulting in high density of the local measurement points. On the other hand side problems linked deviation of the streamlines from direction perpendicular to the hydrometric section plane occur. Under such circumstances the use of CFD flow analysis methods in order to determine the streamline deviation angles is of essential significance.

Application of CFD calculations is recommended also in case of measuring discharge with current-meters installed in short intake penstocks of hydraulic turbines. Fig.9 shows a framework with current-meters situated along the calculated streamlines.

Fig. 8 Frames with fixed the current meters for traversing the hydrometric section.

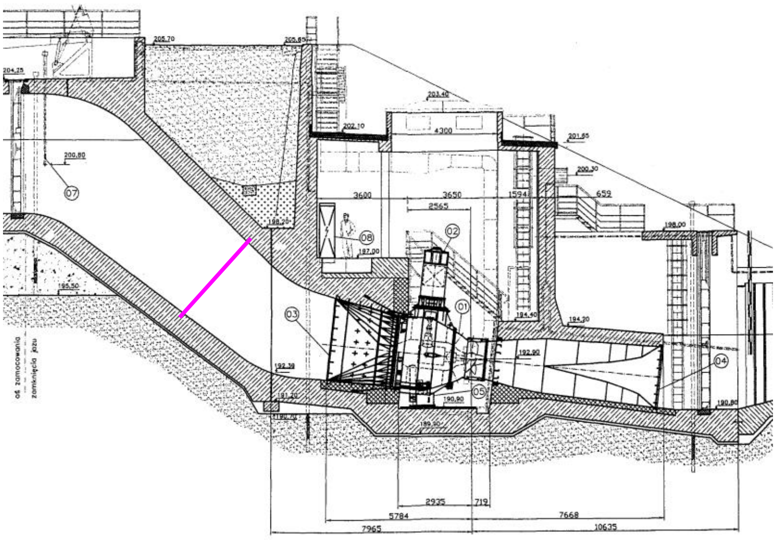

Fig. 9a Vertical section through a unit with hydrometric section indicated.

Fig. 9b Hydrometric section with the supporting frame and installed current-meters

3. THE PRESSURE-TIME METHOD OF FLOW RATE MEASUREMENT (GIBSON METHOD)

3.1. The theoretical principle of the pressure-time method (Gibson method)

The pressure-time method (water hammer or Gibson method) is based on measuring the time-history of pressure difference changes between two hydrometric sections of the conduit during full stoppage of the liquid stream with the aid of a cut-off device. Fig. 10 shows a scheme of turbine penstock with marked hydraulic sections applicable for use in the Gibson method. 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 during stoppage of the stream of liquid - pressure difference caused by inertia force. It can approve that the area between the pressure difference time-history curve recorded during the time of 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. 11.

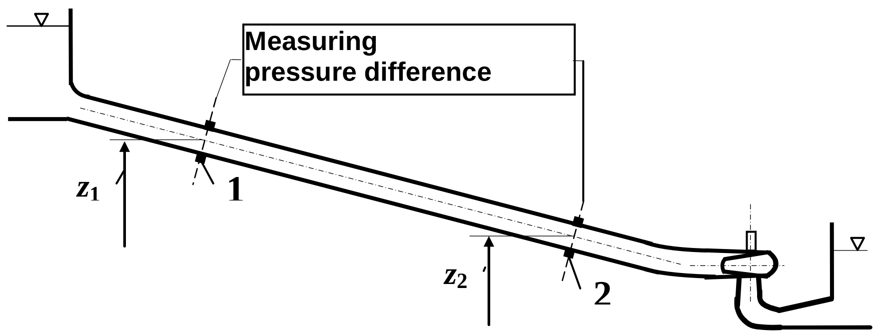

Fig. 10 Scheme of turbine penstock with marked hydraulic sections applicable for use in Gibson method.

According to the theoretical principle of the pressure-time method, the volumetric flow rate Q_0 under initial conditions (before the water flow stoppage was initiated) can be calculated from the following well-known integral formula:

$$Q_0 = \frac{1}{\rho F} \int_{t_0}^{t_k} \left(\Delta p(t) + \Delta p_d(t) + \Delta P_f(t) \right) dt + q_k \qquad (1)$$

where q_k is the flow rate in the final conditions, $\tilde{t}$ actual time, $[t_0, t_k]$ time interval in which the flow conditions change from initial to the final ones, Δp static pressure difference between pipeline sections 2 and 1, Δp_d dynamic pressure difference between pipeline sections 2 and 1, ΔP_f the pressure drop caused by friction losses between sections 1 and 2, ρ liquid density, and finally, F geometrical factor of the examined pipeline segment between pipeline sections 2 and 1 of length L and defined by the following formula:

$$F = \int_0^L \frac{dx}{A(x)} . \qquad (2)$$

The flow rate in the final conditions (q_k), if different from zero due to leakage in the closing device, has to be measured or assessed using a separate method.

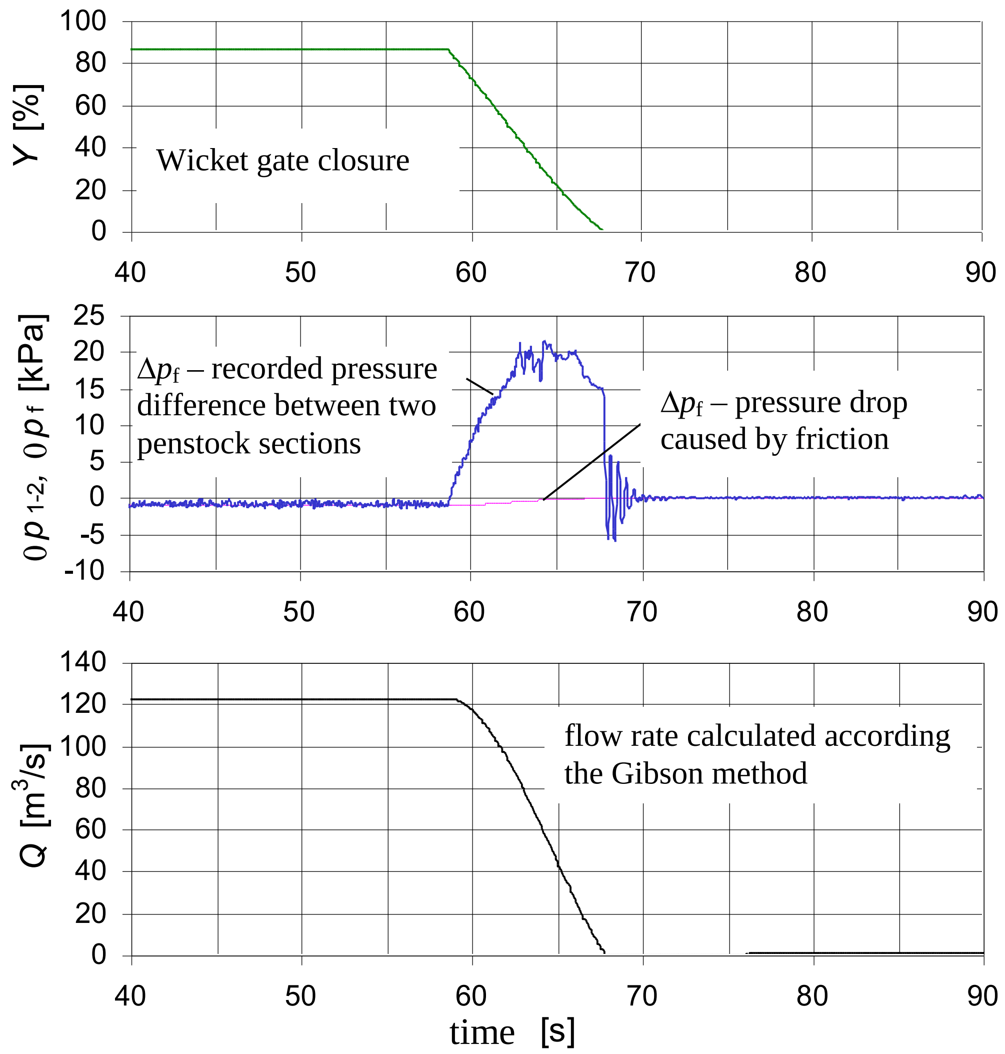

Fig. 11 Example of flow rate measurement using the Gibson method.

The Gibson method was more frequently used in the North America than in Europe and in other parts of the world. At present, the increased accuracy of pressure measurement devices, along with the availability of the hardware for computer acquisition and processing of the measured data are the reason why this method is becoming more attractive also all over the world. The first activities oriented on preparation of its practical use in Poland were taken in the IF-FM, Gdansk, in the second half of the nineties. So far, this method has been used in numerous hydro power plants in Poland and Mexico.

Versions of the Gibson method

In practice, various versions of the Gibson method are used. The most important of them include – Fig. 12:

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 changes 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 constant pressure in the open liquid tank, to which the conduit is directly connected.

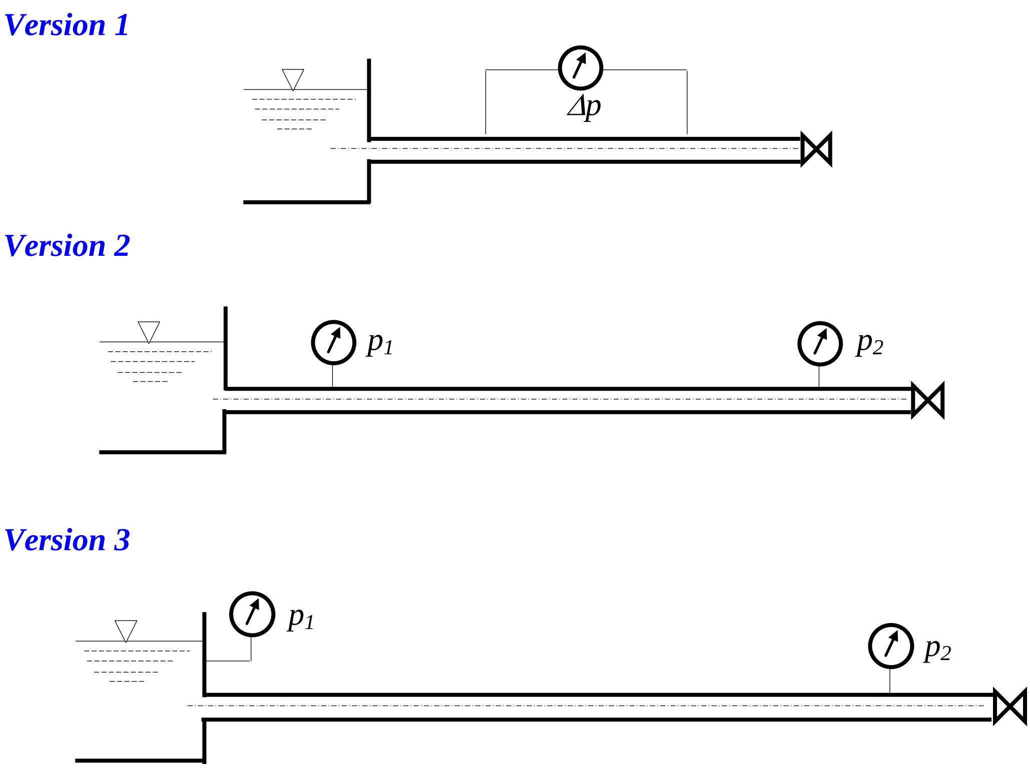

Fig. 12 Various versions of the Gibson method

Some problems which have to be solved during applications of the Gibson method

The influence of a curved penstock application on flow rate measurements

Following the classical approach (version 1), the pressure-time method applicability is limited to straight cylindrical pipelines with constant diameters. However, the International Standard IEC 60041 does not exclude application of this method to more complex geometries, i.e. curved pipeline (with elbows). It is obvious that a curved pipeline causes deformation of the uniform velocity field in pipeline cross-sections, which subsequently causes aggravation of the accuracy of the pressure-time method flow rate measurement results – Fig. 13. So, the influence of a curved penstock application on flow rate measurements by means of the considered method should be taken into account. The IMP PAN group has developed the special calculation procedure for that problem solution [7]. The procedure is based on the CFD *(Computational Fluid Dynamic)* simulation – Fig. 14. It allows calculating the equivalent value of the geometry factor *F* (see Eq. 1) 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. For example, the systematic uncertainty caused by neglecting the effect of the two elbows on flow rate measured values has been estimate – Fig. 15. An example of application of this method to a complex geometry (two elbows in a penstock) was presented.

Similar approach, based on the *CFD* simulation, is needed for determining the value of *F* factor for whole penstock while the version 3 of the pressure time method is used. In the IMP PAN one strives for development of a special procedure for this purpose. It is assumed that this procedure should allow for applying version 3 of Gibson method in penstocks shorter than it follows from current requirements of the IEC 60041 standard – in addition to increasing measurement accuracy of this method.

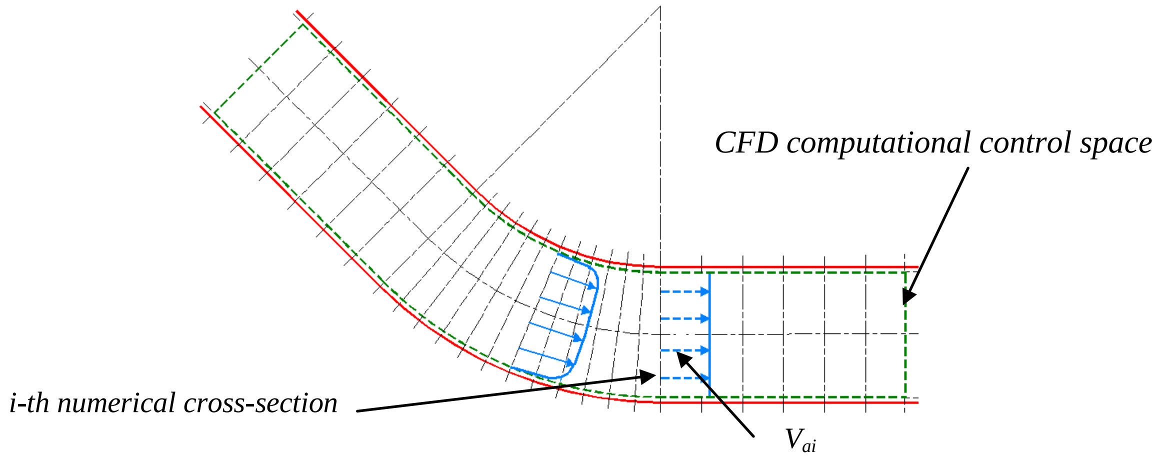

Fig. 13 A pipeline elbow with marked computational space.

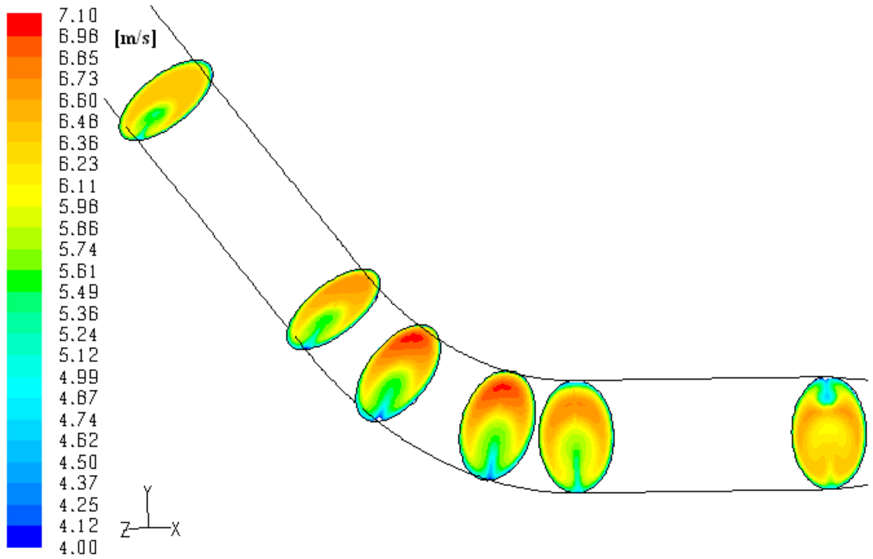

Fig. 14 The velocity magnitude distributions in the penstock cross-sections within the elbow no. 2 for mass flow 200000 kg/s (Q = ~200 m^3/s).

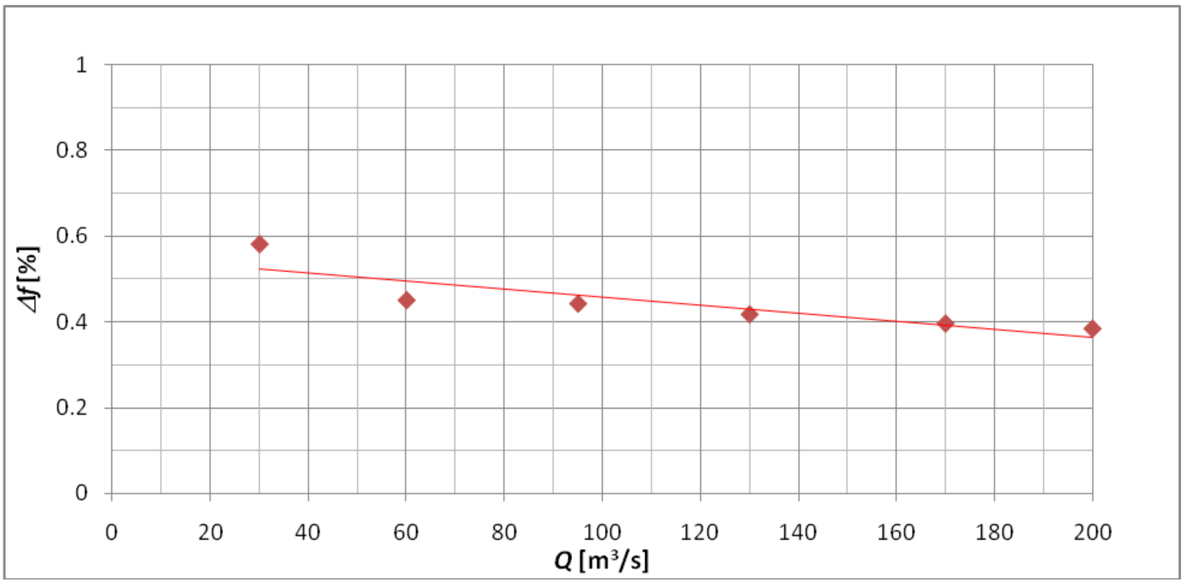

Fig. 15 The values of Δf deviation factor F determined for the assumed flow rate values.

Using the Gibson method based on special instrumentation installed inside penstocks

Flow measurement using the Gibson method typically involves mounting instrumentation on the outside of the penstock. In the case of a plant where the penstock is embedded in concrete traditional use of that method is not possible. Therefore, the IMP PAN measuring group developed an innovative approach that involved installing flow measurement instrumentation inside the penstock. The first application of this group in this range is presented below.

A scheme of the flow system is shown in the Fig. 16. The flow rate was measured using the Gibson method in the version based on separate pressure difference measurements in two hydrometric sections of the penstock. In each of those sections, 4 pressure reception points were prepared, which were linked by tubes with 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 reception points, 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. 17 and 18. The figure 18a shows one pressure reception point, having the form of a piezometric hole drilled in a flat bar. The flat bar was welded to the penstock outer case, following the flow direction. Four pressure reception points were connected, using copper tubes, to the manifold, inside which the absolute pressure transducer of 0.1 class was hermetic mounted. It is worth stressing that preparing the pressure measuring system inside a penstock of 6 m in diameter and inclined by an angle of 40^0 degrees was an extremely difficult task.

Fig. 19 shows: the time-histories of the measured static pressures in the selected hydrometric sections, the static pressure difference determined from them, an the calculated flow rate.

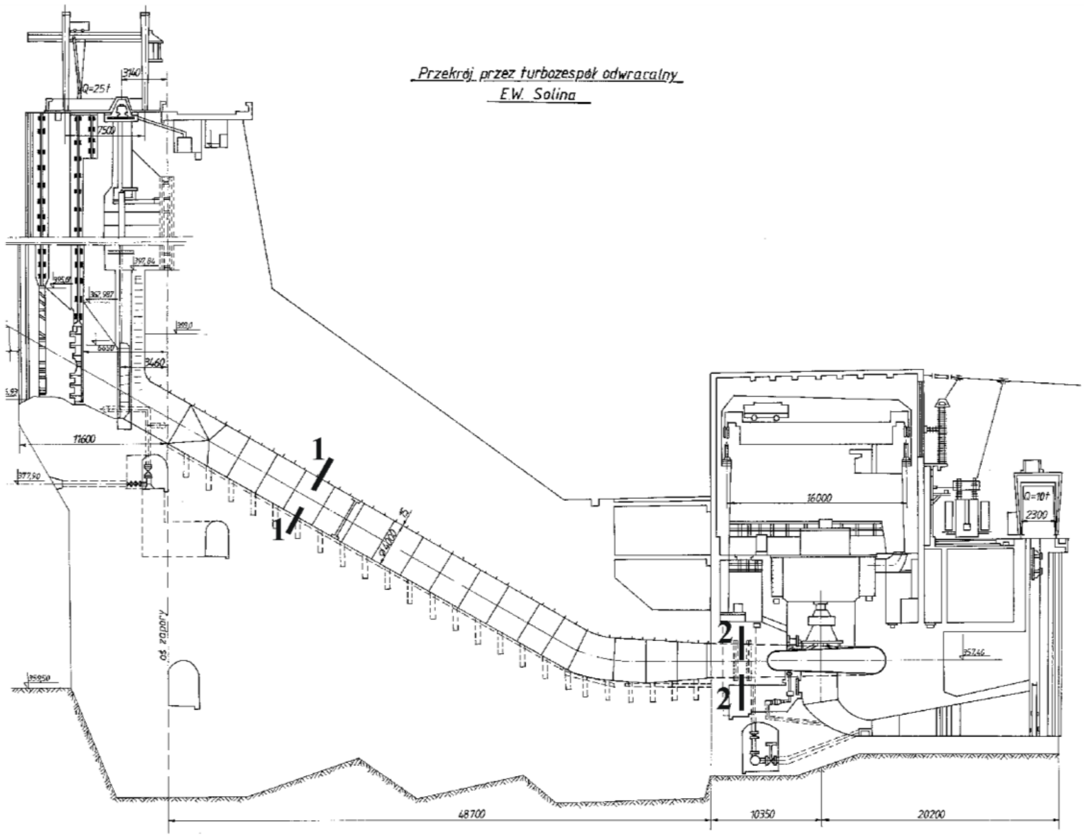

Fig. 16 A scheme of the flow system in the Solina HPP

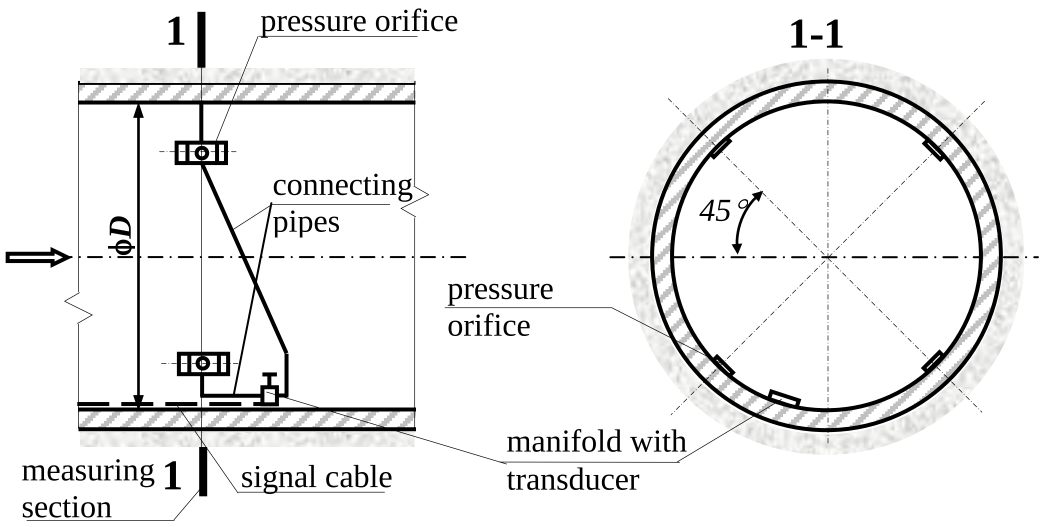

Fig. 17 Distribution of pressure reception orifices in section 1-1 and their connection to hermetic manifold with absolute pressure transducer installed inside.

a)

b)

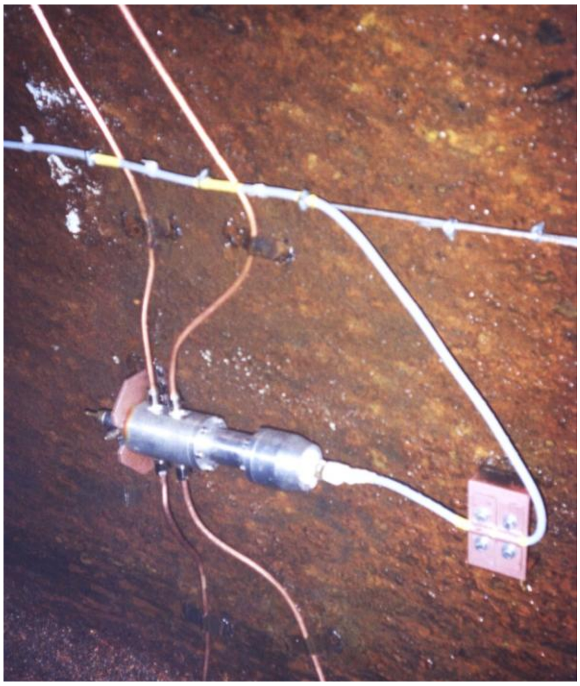

Fig. 18
a) View of the plate with a pressure reception orifices used in measuring section 1-1; b) the manifold installed inside penstock (section 1-1) with the mounted absolute pressure transducer.

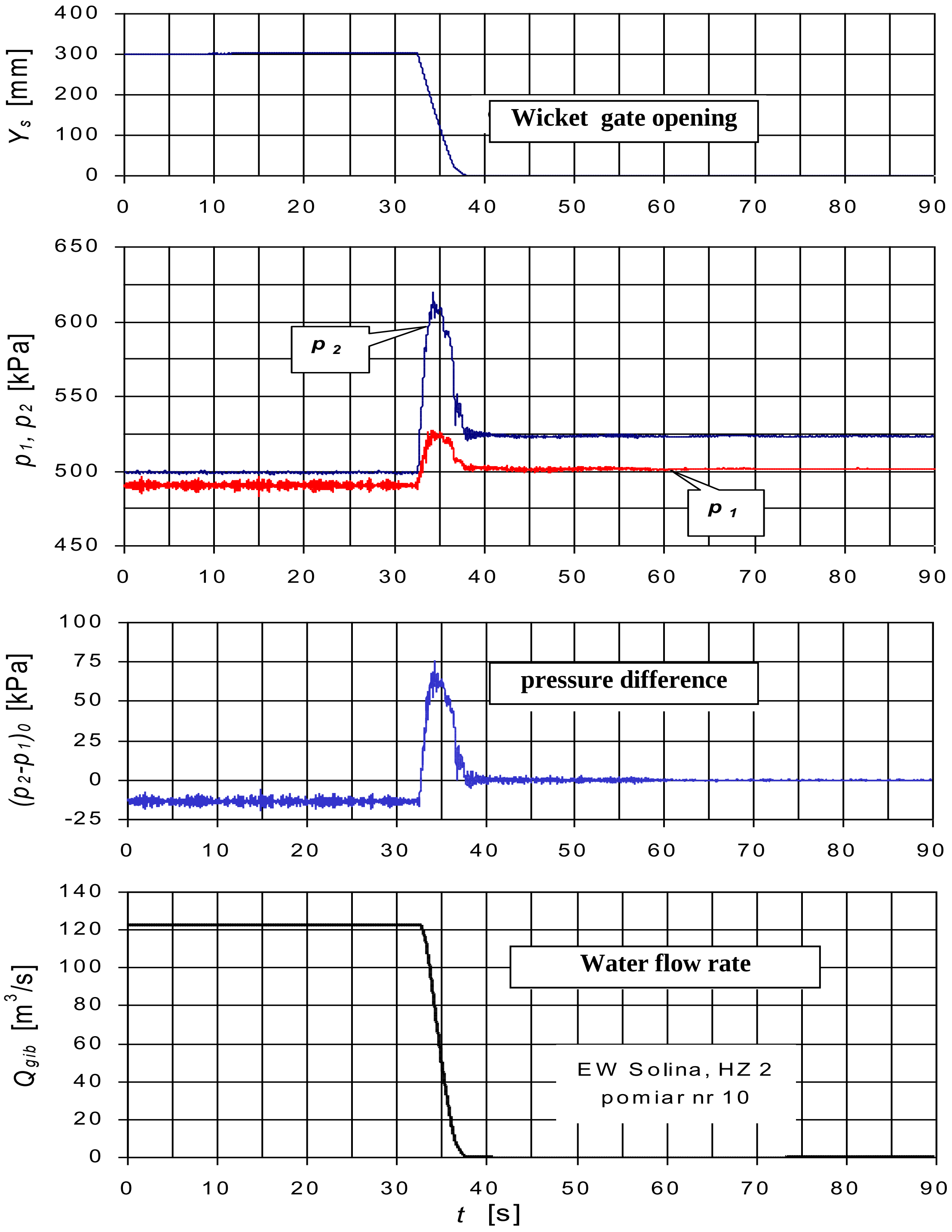

Fig. 19 Pressure changes measured in the measuring sections of the classical turbine penstock, and the flow rate determined from them.

Conclusions relating to the Gibson method

1. At present, among the classical methods, the Gibson method is the one most frequently used. High accuracy of electronic devices used for pressure and pressure difference measurements, along with the availability of software for computer recording and numerical processing of measurement data, made this method more attractive than in the past, when classical techniques were used.
2. Not all theoretical issues of the Gibson method have been solved comprehensively. One of those unsolved issues concerns calculation of friction loss during the unsteady flow of liquid in closed conduits. The method adopted for calculating this loss, justified for the steady-state flows, should be verified in unsteady conditions.
3. To achieve the expected accuracy of the measurement, the selection of conditions in which the method id used, along with the measuring devices applied, should be based on the measurement uncertainty analysis, recommendations given in relevant standards, and personal experience gained.
4. The advantages of the Gibson method with respect to other methods:

   • low cost and easy installation of the measuring system,

   • measurement accuracy close to that of other classical methods,

   • possibility of determining the flow rate time-histories (the majority of those methods do not reveal this much-desired quality).

   Disadvantages of the Gibson method:

   • required assessment or measurement of leakage flow in the flow cut-off devices,

   • required fast closure of the flow cut-off device during each measurement.

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Problems of assessing technical state, strength and lifetime of hydraulic turbine flow system components

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1. INTRODUCTION

This part of paper presents principal information about engineering techniques for assessing and evaluating flow components of water turbines and their systems, generally steel penstocks, spiral cases and draft tubes.

Visual and ultrasonic examinations for wall thinning and pitting of flow components of water turbines and their systems are usually performed. Radiography of welded joints after their finish is now used as a standard activity. Visual tests (VT) and ultrasonic measurements (UT) of wall thicknesses should allow to evaluate corrosion process of materials.

Tensile tests for the parent steel and sometimes weld or riveted joints should be performed to get allowable stress limits which are employed to prevent failure caused by ductile rupture from overstressing.

Stress analyses of the most loaded flow components should be performed very detailed. The quality of this analysis is often check by stress measurements using strain gages.

Flow components should be assessed for both flow-induced and equipment-induced vibrations. Resonant vibrations can cause material fatigue and may results in construction rapture if not corrected. A fatigue evaluation should be considered if significant vibration is observed.

If flaws are present in the weld or based materials, a fracture mechanics evaluation will indicate the critical cracks geometry and size that will cause instability and results in fracture.

2. TECHNIQUES (METHODS) FOR VISUAL AND NON-DESTRUCTIVE EXAMINATION

An initial and basic assessment is performed to determine the current physical conditions and geometry of evaluated components. Information from this initial stage is used to plan a more detailed assessment. The degree of corrosion and erosion, as well as the condition of the coating and lining, are very important.

Table 1. Summary of nondestructive examination techniques.

Examination Technique	Application	Advantages	Limitations
Visual (VT) (Surface Method)	Areas that have discontinuities on the surface.	Economical, expedient, requires relatively little equipment for most applications.	For surface conditions only; dependent upon subjective opinion and visual acuity of personnel performing the examination.
Magnetic Particle (MT) (Surface Method)	Surface and near – surface	Relatively economical and expedient. Portable equipment. Unlike liquid penetrant, can detect some near surface defects. No size restriction. Indications may be preserved on transparent tape.	Used on magnetic materials only; surface roughness may distort magnetic field; parts must be cleaned before and after inspection; some applications require some parts to be demagnetized after inspection; requires use of electrical energy for most applications; normally no permanent record.
Liquid Penetrant (PT) (Surface Method)	Surface defects only.	Detects very small, tight, surface imperfections, easy to apply and to interpret; inexpensive; requires no electric energy except for light source; can be used on both magnetic and nonmagnetic materials.	Surface films such as coatings, scale, or smeared metal can hide or mask rejectable defects. Parts must be cleaned before and after inspection; somewhat time consuming; normally no permanent record.
Ultrasonic (UT) (Volumetric Method)	Size and position of internal and surface defects.	Extremely sensitive; use restricted only by very complex weldments; can be used on all materials; test results known immediately; portable; usually does not require an electrical outlet; high penetration capability; reference standards are required; permanent record.	Demands highly developed interpretation skills; surface conditions must be suitable for coupling to transducer; couplant required; small welds and thin materials difficult to inspect; plane of laminar defects must be normal to beam.
Radiographic (RT) (Volumetric Method)	Size of internal and surface defects; limited by direction of discontinuity.	Provides permanent record; applicable on all materials.	Radiation is a safety hazard; equipment, set up, and gamma sources are expensive; requires highly skilled operating and interpretive; usually not suitable for fillet weld inspections; generally cannot detect laminations; backing bars lead to confusing results; access required on both sides of the surface to be examined; film exposure and processing important; slow, expensive.

The main techniques (methods) using for an initial assessment are as follows:

- Visual (VT)
- Liquid Penetrant (PT)
- Magnetic Particle (MT)
- Ultrasonic (UT)
- Radiography (RT).

The above mentioned non-destructive examination techniques include both surface and volumetric methods. Surface methods, such as visual, magnetic particle, and liquid penetrant examination techniques, are used to define the characteristics of surface indications present in the flow component structure. Volumetric method, such as ultrasonic and radiographic examination techniques, interrogate the entire volume of material to be examined, thus providing a picture of surface or subsurface defects.

The use of surface versus volumetric methods is dictated by the data to be obtained. For example, if a penstock defect is defected during the visual inspection, a magnetic particle examination could be considered to enhanced the visual inspection results and quantify the dimensions of the defect. If defect depth is of concern, an ultrasonic examination technique could be used to quantify depth.

The advantages, disadvantages, and limitations of each techniques are presented in the Table 1

3. DESTRUCTIVE TESTING - MATERIAL AND WELD JOINT TESTS

Older construction of HPPs often may require evaluations of material of unknown specification, mechanical properties, or composition. Also, joint efficiencies may need to be determined for purposes of evaluating the ability to safely operate at current operational parameters. A successful evaluation or a determination of joint efficiency (by comparing the joint strength to the base material) requires knowledge of the mechanical properties of the base or joint material. A piece of the material should be taken to a laboratory for analysis. Appropriate testing may be performed to determine the chemical composition, weldability, tensile properties, and toughness of the material.

Destructive testing is relatively expensive because it involves (expect of the material tests) the removal of material, repair of the area that has been removed, and repair of the coating material.

4. STRESS AND STRENGTH ANALYSIS

Nowadays, the modern methods for evaluating strength of mechanical components are based on the commercial codes using Finite Element Method (FEM). Usually they give reliable results of numerical prediction. Practically in hydro power plants they are often use in the problem of assessing and strengthening the weakness (crucial) places.

As an example, the strength analysis of penstock bifurcation (Fig. 1) in a small hydropower plant is presented below.

The stress magnitude in a pipeline bifurcation is usually 3-7 times greater than in regular pipeline shells [7,8,9,10]. Special reinforcements are provided in order to decrease the stress concentration in crucial spots [7,9].

The penstocks of hydropower plants built in the first half of the twentieth century are rarely equipped in such kind of reinforcement. The lack of reinforcement can result penstock failure, especially under sudden pressure rise conditions. The failure of the penstock in Lapino hydropower plant (Poland) can be a good example of the related strength problems [1]. The penstock rupture took place at the connection of the penstock with the turbine inlet pipe during turbine load rejection.

The below presented results of strength analysis of a hydropower pipeline bifurcation consisted of the following parts:

- determination of the maximal internal pressure, e.g. during turbine load rejection,
- determination of the mechanical properties of the pipeline shell material and rivet or weld junction,
- stress analysis of the pipeline shell for assumed loading and material properties.

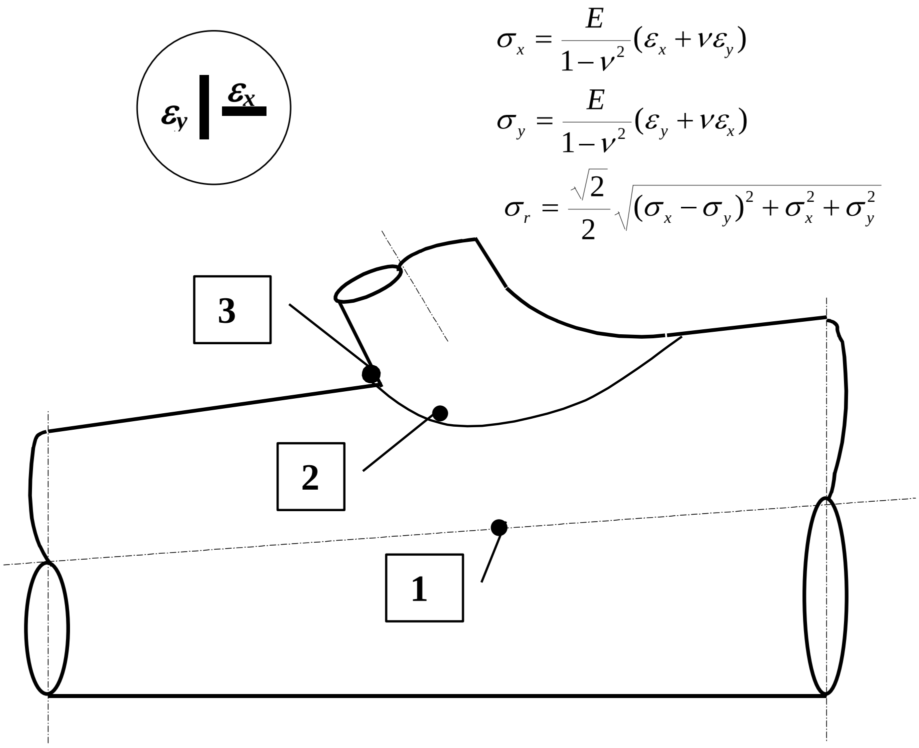

Fig. 1 Layout of bifurcation and places selected for strain measurements

The pressure loading was determined theoretically and experimentally. In the first case, a special computer code developed in the Institute of Fluid-Flow Machinery of the Polish Academy of Sciences (IMP PAN) for prediction of water hammer in pipeline systems of hydraulic machines is used. The code has been validated using numerous experimental results. One of the example is presented in Fig. 2.

Mechanical properties of the material were obtained by means of the standard tensile strength tests, provided that sufficient material samples can be taken from the penstock shell. In other cases, the mechanical properties are estimated by means of chemical tests and metallographic investigation.

The complex stresses distribution in the analysed penstock shell was calculated by means of commercial codes (like ADINA, ABAQUS , NASTRAN) utilising the FEM – Fig. 3. The calculation drew on measured geometry of the penstock segment and strength properties of the material found from the material tests. Components of the calculated stress field were substituted with the equivalent stresses according to the Huber/Henkey/von Mises (HMH) theory.

The obtained results show very unfavourable distribution of stresses in the analyzed segment of the penstock shell. The connection of the inlet pipe with the main branch of the penstock is featured by significant concentration of stresses. The stress concentration coefficient, a ratio of the maximum stress value to the stress prevailing in the uniform conical segment, is about 8. This result coincides with the values often quoted in the literature [7]. Old reinforcements of fin shape situated perpendicularly to the line of penstock - inlet pipe junction are not good solution - are ineffective.

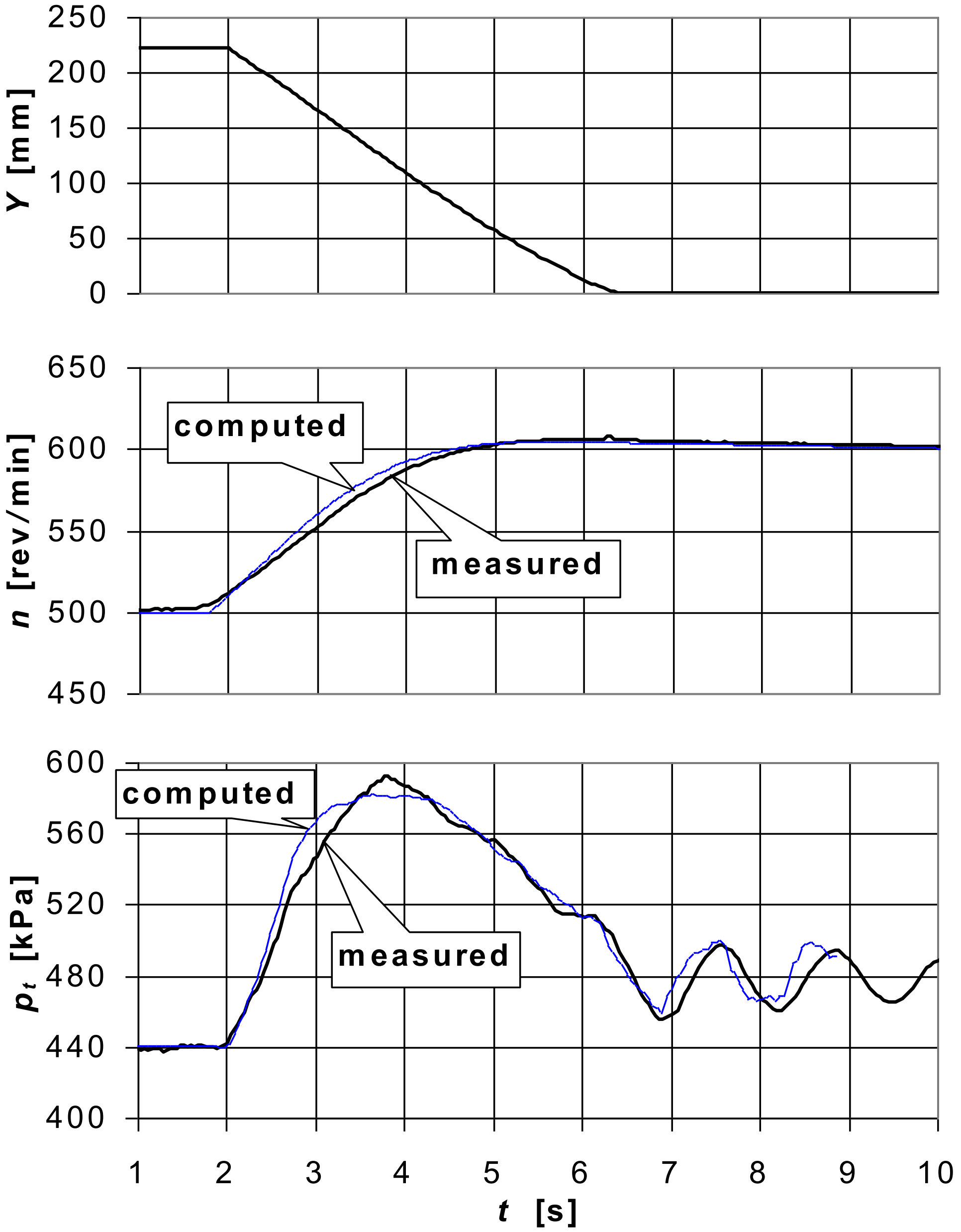

Fig. 2 The comparison between the recorded and calculated curves of pressure in the penstock (p_t) and runner speed (n) during a load rejection.

In order to reduce high stress level and fulfil the safety requirements the collar reinforcement shown in Fig. 4 has been recommended and applied. Such solution reduced twice the maximal existing stresses under the steady-state rated loading and reduced these stresses below the yield point under the maximal assumed loading.

Mainly for the verification of the numerical results, strain gauge measurements are applied in the selected crucial points of the bifurcations.

The results of measured and calculated equivalent stresses, presented in Table 2, show good correlation between the measurement and calculation results.

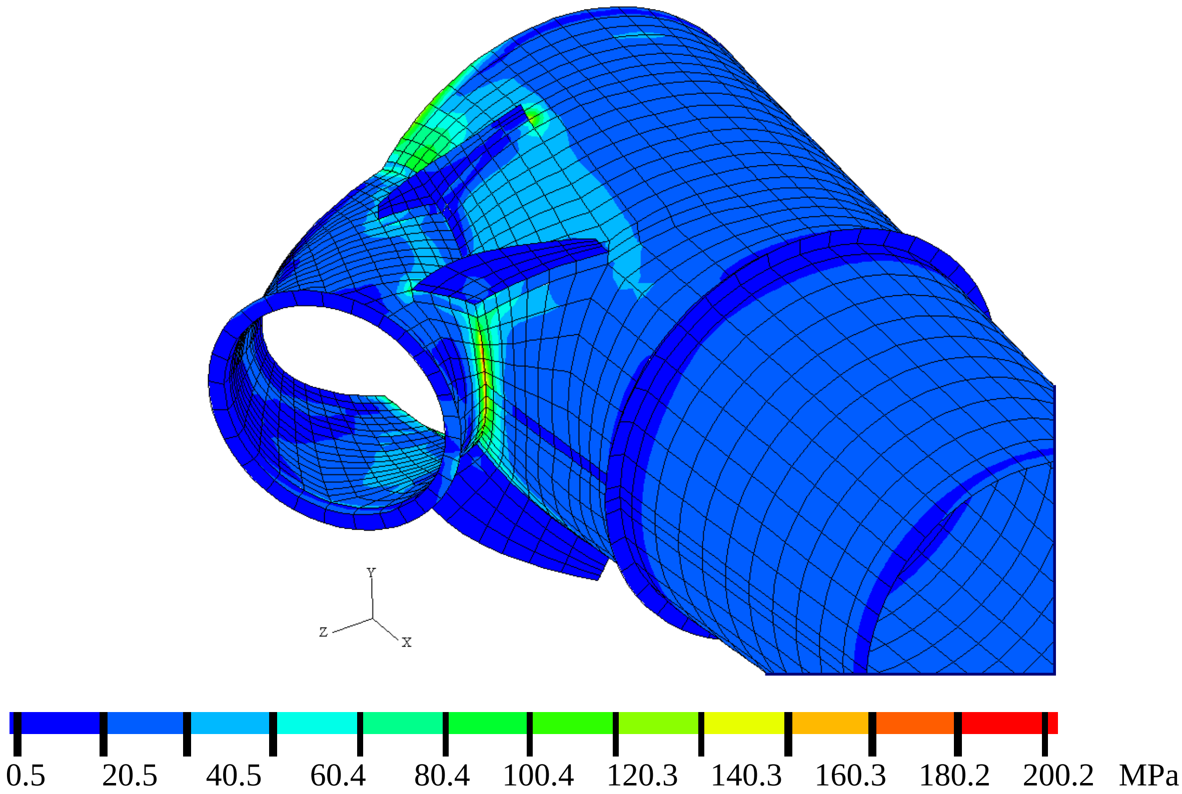

Fig. 3 Penstock bifurcation with old reinforcements of fin shape situated perpendicularly to the line of penstock – inlet pipe junction. Distribution of the equivalent stresses (HMH) at the *external side* of the penstock shell under pressure load of p = 415 kPa (material model: linear elastic).

Table 2. Comparison of the measured and calculated equivalent stresses (ADINA code)

	Equivalent stresses under the steady-state rated loading of 415 kPa		
	S_{1r}	***S_{2r}***	***S_{3r}***
	MPa	MPa	MPa
Experiment	**39.6**	**149.1**	**247.5**
Calculation	**37.5**	**141.4**	**240.0**

New reinforcement collar (rib).

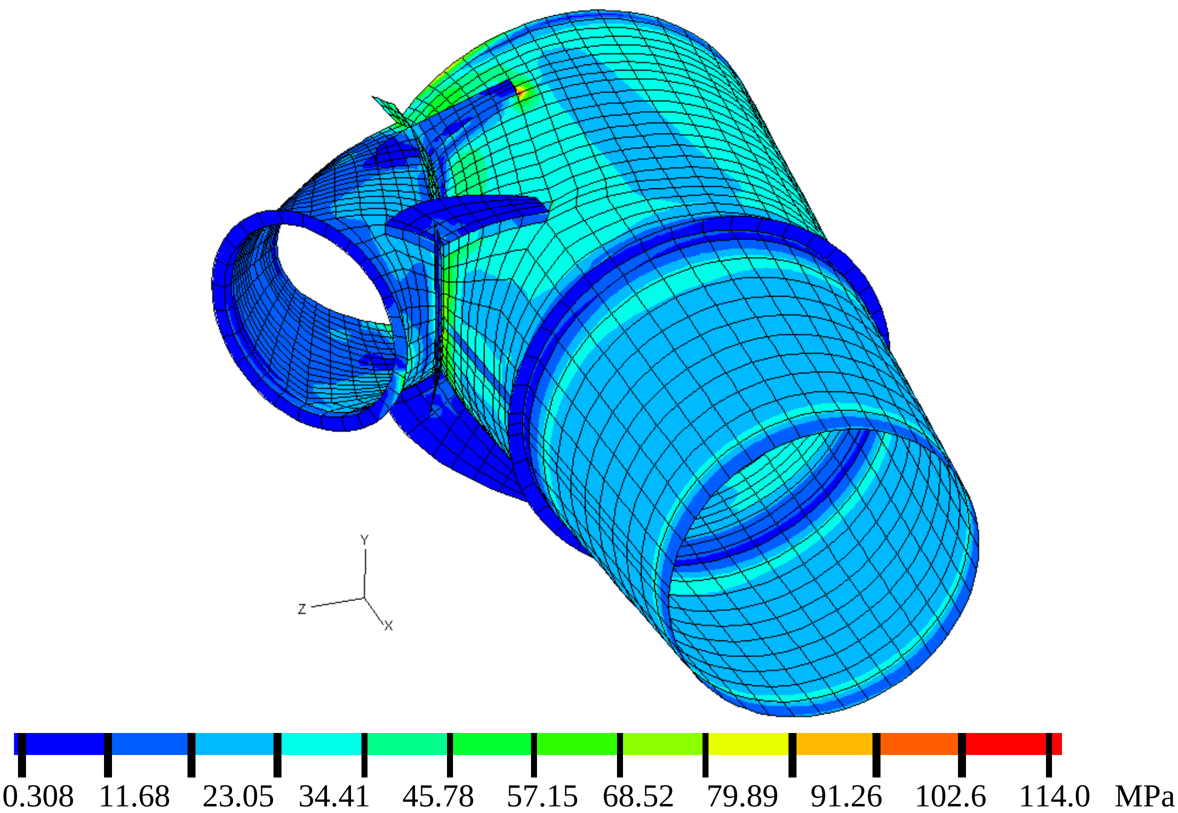

Fig. 4. Penstock bifurcation with used collar reinforcements and existing reinforcements. Distribution of the equivalent stresses (HMH) at the external side of the penstock shell under p= 415 kPa pressure load (material: linear elastic).

5. VIBRATION ANALYSIS

Significant vibrations of mechanical constructions are very danger from safety point of view. We can meet vibration induce by flow or equipment element. Total flow system of a HPP should be assessed for both flow-induced and equipment-induced vibrations. Resonant vibrations can cause material fatigue and may results in construction rapture if not corrected. A fatigue evaluation should be considered if significant vibration is observed.

Example:

Fig 5 shows very dangerorous situation happened in a certain water turbine flow system under partial loading when the excessive pressure pulsations were induced. The reason of this is the resonance of the pressure pulsation in the draft tube (caused by vortices) with the main waterhammer frequency in the penstock of the tested turbine. Analysis has indicated that the frequency of pressure pulsation induced by vortices in the draft tube is about twice higher than the frequency of the waterhammer phenomenon.

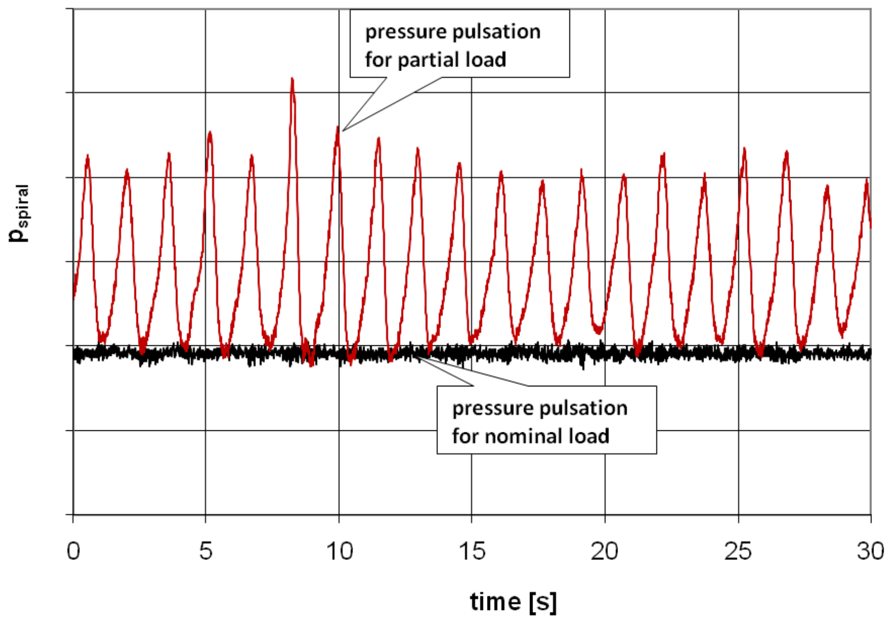

Fig. 5 Pressure-time variations in a turbine spiral case recorded during steady-state operation with nominal and partial load.

CONCLUSION

- The non-destructive examination techniques, such as visual, ultrasonic, magnetic particle, liquid penetrant and radiographic examination methods, should be used to discover surface or subsurface defects of the material of flow components.
- Destructive Testing is recommended to be performed if the material properties are not known. In such cases, coupons should be taken to determine, for instance, the chemical composition, weldability, tensile properties and notch toughness.
- The use of strength analysis of a hydropower flow components is recommended in order to reinforce the crucial places of these components, especially in older HPPs. The investigation results can be helpful when recommending the strengthening precautions to be applied in places of maximum stress concentration in order to prevent material ruptures.
- Flow components should be assessed for both flow-induced and equipment-induced vibrations. Resonant vibrations can cause material fatigue and may results in construction rapture if not corrected. A fatigue evaluation should be considered if significant vibration is observed.

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SMALL HYDRO ACTION
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Układy automatyki, zabezpieczeń i pomiarów oraz zdalnej kontroli pracy bezobsługowej elektrowni wodnej

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Abstract: *The paper describes devices and their functions within the automatic control systems of Smolice Hydropower Plant units.*

1. WSTĘP

Elektrownia wodna Smolice jest całkowicie nową elektrownią wybudowaną na rzece Wiśle przy istniejącym jazie Smolice (Rys.1). Głównym inwestorem i właścicielem elektrowni jest Zespół Elektrowni Wodnych Nidzica. Elektrownia została przekazana do eksploatacji w 2005r.

Rys.1 Lokalizacja EW Smolice

2. DANE TECHNICZNE URZĄDZEŃ WCHODZĄCYCH W SKŁAD HYDROZESPOŁU AWARYJNEGO ZASILANIA

Elektrownia wodna Smolice wyposażona jest w dwa turbozespoły złożone z turbin rurowych z podwójną regulacją, które napędzają przez przekładnie kątowe generatory synchroniczne

Hydrozespół składa się z następujących urządzeń:

A) Elektrownia

Typ	niskospadowa, z jazem
Ilość turbozespołów	***2***
Urządzenie piętrzące	jaz ruchomy
Przepływ	2 x 27 m
Całkowita moc	2 x 542 kW

B) Turbina

Typ	Kaplana, prostoprzepływowa
Producent	MAVEL
Spad roboczy	2,75 m
Moc znamionowa	587 kW
Znamionowa prędkość obrotowa	144 obr/min

C) Generator

Typ:	synchroniczny
Producent:	DOZAMEL
Moc znamionowa:	1375 kVA
Napięcie znamionowe:	660V, 50 Hz
Prąd znamionowy:	1203 A
cos φ:	0,8

3. FUNKCJE REALIZOWANE PRZEZ UKŁADY AUTOMATYKI

Układ automatyki EW Smolice spełnia następujące funkcje:

- samoczynny start/stop elektrowni (w zależności od poziomu wody)
- automatyczny rozruch, odstawianie i regulacja turbozespołu miejscowa lub z punktu dyspozytorskiego
- automatyczna synchronizacja generatorów
- kompletne zabezpieczenia elektryczne i elektromechaniczne generatora i turbiny

4. OPIS UKŁADÓW AUTOMATYKI

Dostarczone przez Instytut Energetyki urządzenia automatyki umieszczone zostały w dziesięciu szafach:

- w szafie nr.1 zainstalowano układy wyprowadzenia mocy do transformatora,
- w szafie nr 2 i 4 zainstalowano układy wyprowadzenia mocy z generatorów,
- w szafie nr 3 i 5 zainstalowano układy zabezpieczeń i pomiarów oraz regulacji napięcia generatorów,
- w szafie nr 6 i 7 zainstalowano układy zasilania potrzeb własnych AC,
- w szafie nr 8 i 9 zainstalowane są układy regulacji turbiny,
- w szafie nr 10 zainstalowany został układ sterowania nadrzędnego oraz układy komunikacji (GSM, GW4).

Schemat strukturalny elektrowni pokazano na rys.2. Moc z obu generatorów jest wyprowadzona na szyny rozdzielni głównej 0,69kV, a z niej za pośrednictwem mostu szynowego do transformatora 15,75/0,69 kV i dalej kablami do rozdzielni sieciowej 15 kV. Rozdzielnia generatorowa 0,69 kV i rozdzielnia 15 kV są zlokalizowane w budynku elektrowni. Transformator wyprowadzenia mocy w izolacji żywicznej w obudowie (stopień ochrony IP23) jest również zlokalizowany na stanowisku w budynku elektrowni. Do zasilania potrzeb własnych 0,4 kV zastosowano transformator 0,69/0,4 kV o mocy 100 kVA także zlokalizowany w pomieszczeniu elektrowni.

Jako rezerwowe zasilanie potrzeb własnych wykorzystano lokalną sieć 0,4 kV tj z rozdzielni niskiego napięcia stacji transformatorowej 15/0,4 kV „Smolice Śluza”. Szczytowy pobór mocy dla zasilania rezerwowego może wynosić do 120 kVA.

- **regulator napięcia generatora**

Regulator napięcia typu RNGA–54n jest tyrystorowym układem regulacji napięcia o zasilaniu napięciowo-prądowym. Przeznaczony jest do współpracy z bezszczotkowymi generatorami wyposażonymi we wzbudnicę z wirującym prostownikiem diodowym.

Człon sterujący składa się z następujących podzespołów:

- transformatorów pomiarowych napięcia i prądu generatora TPN
- cyfrowego regulatora RC
- zasilacza PTI
- członu sterowania układu wzbudzenia do prób generatora TS

Cyfrowy regulator RC-12 realizuje następujące funkcje:

- regulacji napięcia generatora lub kompensacji prądowej, która zapewnia właściwy rozdział mocy biernej między generatory pracujące równolegle,
- regulacji napięcia generatora lub cos φ
- regulacji prądu wzbudzenia wzbudnicy po zaniku napięcia pomiarowego generatora tj. po otwarciu wyłącznika F11,
- ogranicznika minimalnego prądu wzbudzenia chroniącego generator przed nadmiernym wzrostem mocy biernej pojemnościowej i utratą stabilności statycznej,
- ogranicznika prądu stojana, chroniącego stojan przed przeciążeniem (działa ze zwłoką czasową),

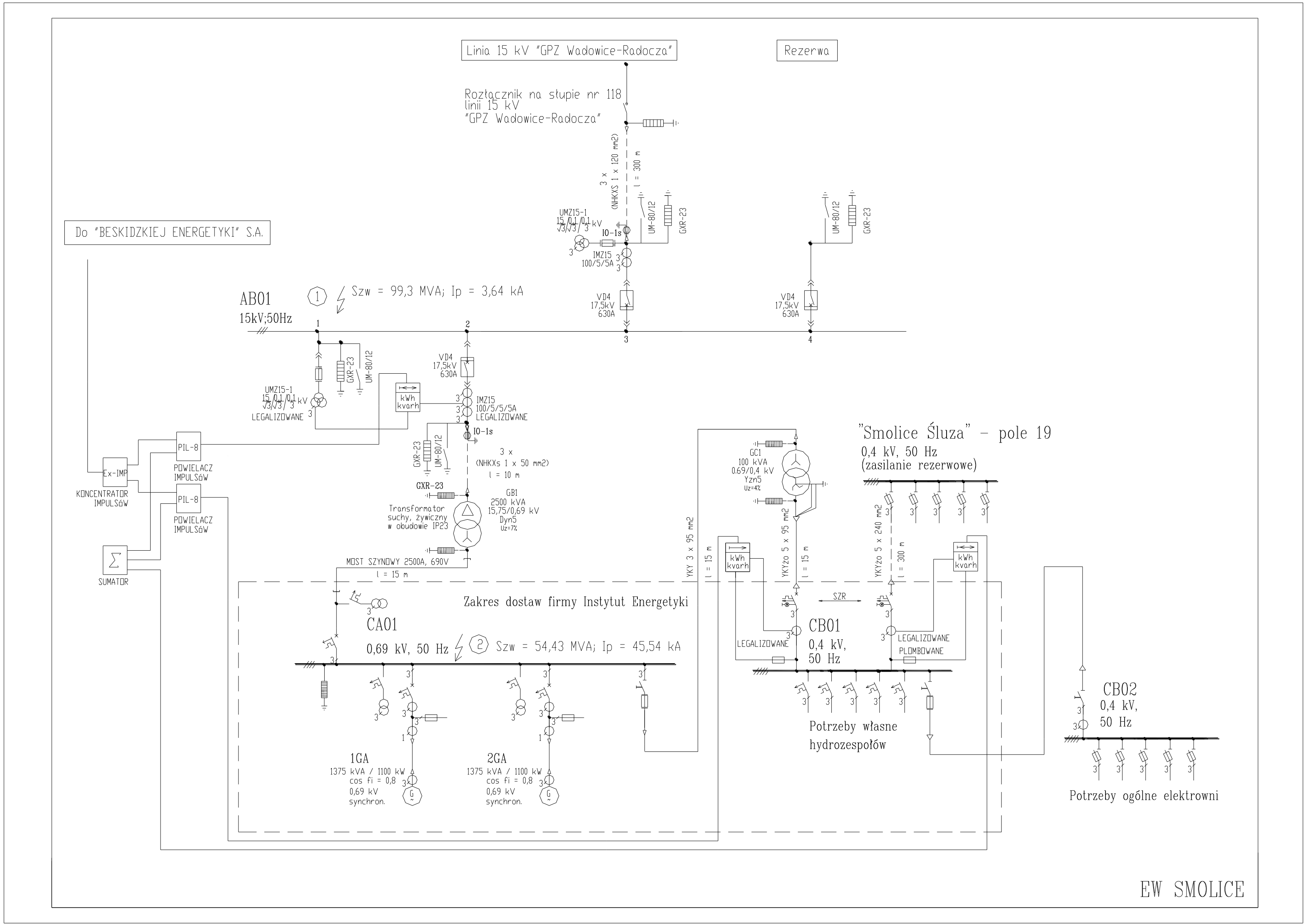
- ogranicznika indukcji chroniącego generator przed wzrostem indukcji w żelazie podczas przypadkowego obniżenia częstotliwości maszyny (U/f = const),
- ogranicznika prądu wirnika generatora, chroniącego wirnik przed przeciążeniem (działa ze zwłoką czasową),
- wykrywania i sygnalizacji zakłóceń i uszkodzeń,
- szeregowej komunikacji RS-485 pozwalającej na współpracę z układem nadrzędnym,
- układu sterowania tranzystorem mocy IGBT 1V1,
- zabezpieczenia od skutków zwarć wirujących diod wzbudnicy (wysyła sygnał na wyłączenie i odwzbudzenie generatora)
- sterowania wyłącznikiem wzbudzenia i stycznikiem wzbudzenia wstępnego.

- **układ zabezpieczeń i synchronizacji generatora**

Zabezpieczenie generatora wykonane jest w oparciu o wielofunkcyjne programowalne cyfrowe układy MFR2 produkcji Woodward Governor Company Leonhard-Reglerbau GmbH. Jeden przekaźnik typu MFR2 realizuje komplet funkcji zabezpieczeń generatora a ponadto pełni rolę synchronizatora i analizatora sieciowego. Przekaźniki komunikują się z systemem nadrzędnym, poprzez konwerter GW4 (sieć CAN) jak i sygnałami dwustanowymi. Po zadziałaniu poszczególnego zabezpieczenia jego wyjście pobudza przekaźnik pośredniczący, który swymi stykami pomocniczymi równocześnie wyłącza wyłącznik główny i wyłącznik wzbudzenia. Jednocześnie z pobudzonego zabezpieczenia wysyłany jest sygnał dwustanowy na zatrzymanie turbiny.

Przekaźnik zabezpieczenia pełni m.in. następujące funkcje:

- podnapięciowe (ANSI 27)
- nadnapięciowe (ANSI 59)
- podczęstotliwościwe (ANSI 81U)
- nadczęstotliwościowe (ANSI 81O)
- nadprądowe (ANSI 50)
- składowej przeciwnej prądu (ANSI 46)



Rys.2. Schemat strukturalny EW Smolice

- **regulator turbiny**

Do zadań regulatora turbiny typu RTRS–21 należy sterowanie sekwencjami uruchamiania i odstawiania turbozespołu.

Cyfrowy regulator hydrozespołu typu RTRS-21 zapewnia:

- jednoimpulsowe uruchamianie hydrozespołu,
- regulację prędkości obrotowej hydrozespołu na biegu jałowym i podczas synchronizacji,
- regulację obciążenia hydrozespołu przy pracy na sieć państwową według charakterystyki statycznej prędkość obrotowa – otwarcie kierownicy turbiny,
- regulację otwarcia łopatek wirnika turbiny według trójwymiarowej charakterystyki kombinatorowej,
- jednoimpulsowe odstawianie hydrozespołu,
- zamykanie turbiny po zadziałaniu zabezpieczeń,
- zabezpieczenie przed przekroczeniem dopuszczalnej prędkości obrotowej,
- ręczne sterowanie otwarciem łopatek kierownicy i wirnika turbiny podczas prac montażowych, rozruchowych i remontowych,
- komunikację z terminalem operatorskim w zakresie przyjmowania sygnałów sterujących oraz przesyłanie informacji o stanie pracy hydrozespołu oraz o wybranych wielkościach mierzonych,
- komunikację z cyfrowym regulatorem nadrzędnym sterowania i kontroli pracy elektrowni.

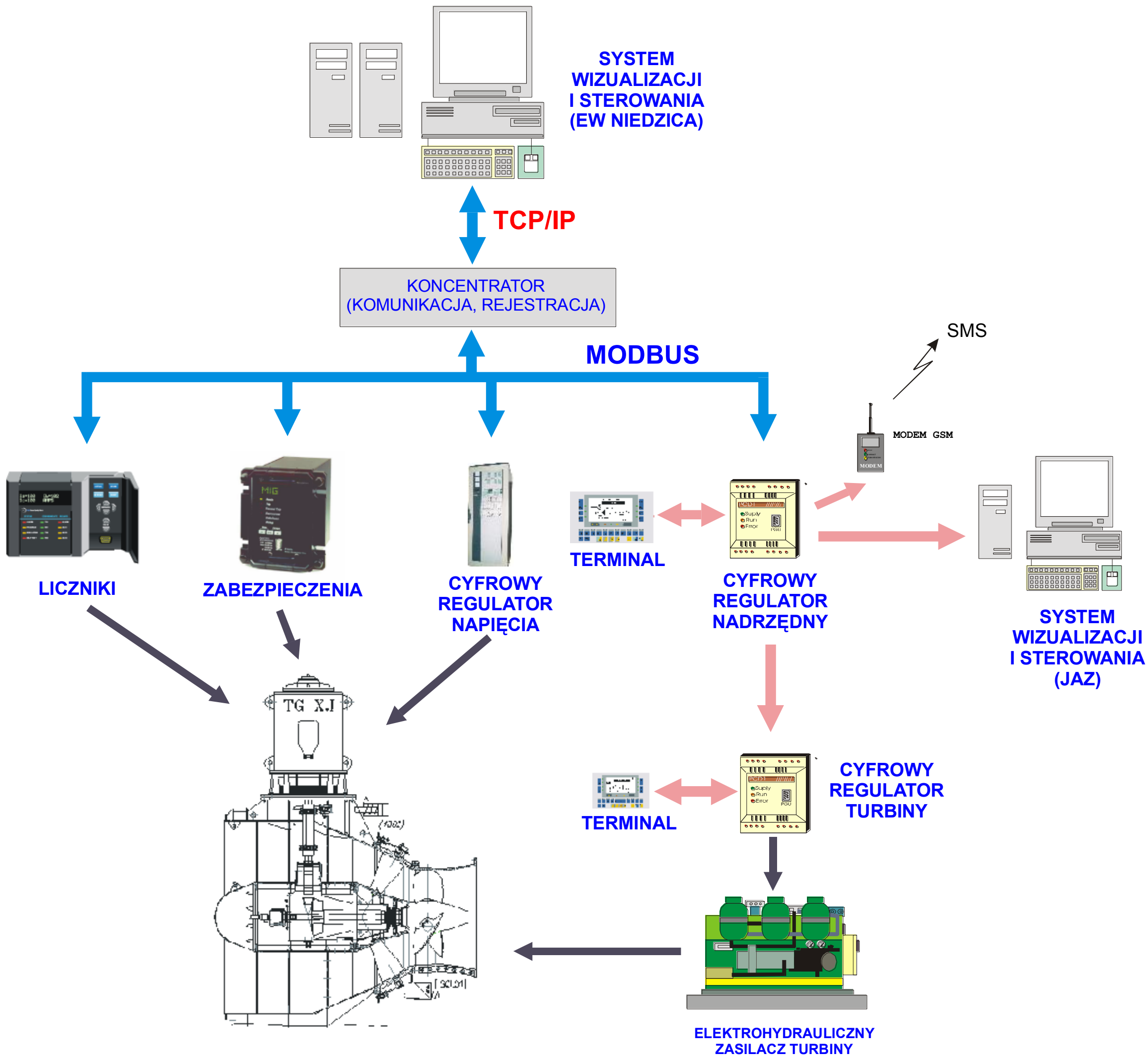
- **układ sterowania nadrzędnego**

Układ sterowania nadrzędnego zapewnia:

- samoczynne uruchamianie i odstawianie turbozespołów w zależności od poziomu wody
- sterowanie pracą i obciążeniem hydrozespołów w zależności od zadanego poziomu wody
- sterowanie, sygnalizację i zabezpieczenia hydrozespołu w powiązaniu z wyposażeniem turbiny i generatora
- komunikację z urządzeniami i prezentację na terminalu wybranych parametrów i komunikatów
- komunikację z modemem GSM i wysyłanie informacji SMS do wybranych użytkowników o stanie pracy elektrowni
- komunikację z systemem SCADA na Jazie
- komunikację z koncentratorem systemu SCADA EW Niedzica

Do sterownika układu sterowania nadrzędnego doprowadzone są dwustanowe sygnały z wybranych wyłączników i rozłączników w celu prezentacji na panelu operatorskim aktualnego stanu rozdzielni. Ponadto doprowadzone są dwustanowe sygnały kontrolujące poprawną pracę innych urządzeń (czyszczarka, krat, SZR, zasilanie itp.). Pomiary poziomów wody oraz ciśnienia atmosferycznego doprowadzone są zarówno do regulatorów turbin jak i regulatora nadrzędnego. Dodatkowo sterownik komunikuje się łączami cyfrowymi z innymi urządzeniami. Strukturę systemu komunikacji układów automatyki pokazano na rys.3.

Praca zespołu nadzorowana jest w EW Niedzica przez systemy dostarczone przez firmy Energotest i ProZap.



Rys. 3. Struktura komunikacji układów automatyki zespołu awaryjnego zasilania

5. OPIS PROCESÓW URUCHAMIANIA I ODSTAWIANIA HYDROZESPOŁU Z AWARYJNEGO ZASILANIA

Przewidziano trzy tryby pracy hydrozespołów:

- regulacja poziomu – regulacja otwarcia w zależności od poziomu wody górnej
- sterowanie otwarcia – praca ze stałym zadanym otwarciem
- regulacja mocy – praca ze stałą zadaną mocą

Rozruch turbiny może być inicjowany miejscowo z panelu sterowniczego, zdalnie z systemu SCADA w EW Niedzica lub automatycznie z regulatora nadrzędnego w przypadku pracy z regulacją poziomu.

Po sprawdzenie wszystkich warunków gotowości następuje m.in. załączenie pompy olejowej i pompy oleju agregatu smarnego , zazbrojenie regulatora, a następnie otwieranie kierownicy i wirnika do wartości rozruchowej Cały proces przebiega sekwencyjnie i po wykonaniu kolejnych kroków regulator przechodzi do nastepnych.. Turbina rozkręca się do obrotów znamionowych. Po osiągnięciu prędkości obrotowej ok. 90% następuje załączenie wzbudzenia generatora a następnie synchronizatora. Po synchronizacji układ otwiera kierownicę do wartości wypracowanej przez aktualnie wybrany regulator.

Odstawienie turbiny podobnie jak rozruch może być inicjowane miejscowo lub zdalnie. Rozróżnia się dwa sposoby odstawiania turbozespołu: Planowe i Awaryjne.

Planowe odstawienie przebiega w kolejności odwrotnej niż rozruch. Zainicjowanie odstawienia może być realizowane lokalnie (sterownikiem z drzwi szafy lub przez regulator nadrzędny) lub zdalnie (z systemu SCADA w EW Niedzica). Impuls na wyłączenie generatora jest wysyłany po odciążeniu turbiny, gdy otwarcie kierownicy zmniejszy się poniżej wartości odpowiadającej biegowi jałowemu α_o.

Odstawienie awaryjne występuje w przypadku działania zabezpieczeń lub po naciśnięciu przycisku bezpieczeństwa. Możliwe jest również zdalne odstawienie awaryjne z systemu SCADA wykorzystując sterowanie wyłącznikami lub poprzez zabezpieczenie generatora. Sygnał awaryjnego odstawienia pozbawia zasilania rozdzielacz zazbrajający regulatora turbiny, co powoduje zamknięcie kierownicy pod działaniem ciśnienia oleju na siłownik. Równocześnie zostaje otwarty wyłącznik generatora.

6. UWAGI KOŃCOWE

Wykorzystanie cyfrowych układów sterujących w powiązaniu z systemami wizualizacji SCADA pozwoliło na:

- kompleksową automatyzację pracy elektrowni i minimalizację działań obsługi w procesie nadzoru i sterowania obiektem,
- swobodną akwizycję danych pomiarowych oraz łatwy dostęp do nich, co z kolei pozwala na bieżąco analizować i wpływać na pracę obiektu,
- swobodę programowania i dostosowywania do nowych funkcji i zadań w przyszłości.

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Overhaul and rehabilitation of the civil works

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1. INTRODUCTION

Civil works represent, approximately and in common situations, the *40%* of total costs of high head plants and the *60%* of low head plants.

Then they are a relevant item from the economic point of view, the most weighty one!

But they are important not only for their economic relevance; they are also a *crucial technological component* of the plant, as they strongly contribute to the success of the process which transforms the potential energy of the natural source in the most easy-to-use form of energy, such is the electric one. A supply canal or tailrace in low head schemes, as well as a penstock in high head ones, undoubtedly aren't simple foundations or shelters for some electromechanically equipment, like, for example, in thermal, wind or solar plants, but they take active part to the process and dramatically affect the final performances of the plants.

2. THE CIVIL WORKS LIFE

As a common feeling the civil works last forever, more or less!

Actually many existing plants seem to confirm this feeling, as they are operating since many decades without any patent failure in the civil structures.

The fiscal depreciation rate tells us something similar: in Italy it is 1% for the civil works, that means 100 years of technical life, while the fiscal depreciation rate for the electromechanical equipments is 7%, that means 14 years of expected technical life.

We assume a very long life for the civil works, but what about their efficiency, taking into account what we underline in the introduction about their crucial contribution in the process?

Maybe they don't fail for many and many years, but anyway their degradation affects the plant performance as energy production, operating costs, and operating reliability.

3. CIVIL WORKS DEGRADATION: A NATURAL EVOLUTION OR AN ORIGINAL SIN?

In our experience in the rehabilitation of many plants, we face some typical causes of the degradation, which can be basically written down into 3 categories:

1. regular degradation due to natural deterioration processes;
2. unusual degradation due to the natural deterioration process accelerated by an original sin;
3. heavy degradation due to an original sin.

Actually, the boundaries of each category are quite uncertain: an intake which has silting problems every flood season certainly suffers of an original sin, but what about if it happens every 5 years?

4. TYPICAL DEGRADATION IN THE CIVIL WORKS OF A HYDROELECTRIC PLANT

In the table we have summarised the main typologies of degradation in the civil works

4.1 Dams or weirs

4.1.1 Typical problem

Foundations sliding; seepage (underground water flow); leakages (water flow throw the dam body) → stability problems

4.1.2 Original sin

Wrong geological approach in the design/erection phase; design mistakes; erection mistakes (poor quality materials or wrong erection methodologies).

4.1.3 Normal event

Degradation of the waterproof screen.

4.2 Intake structures

4.2.1 Typical problem

Sediments deposition

4.2.2 Original sin

Wrong hydraulic design both of the structures layout referring to the river morphology and of the flushing devices.

4.2.3 Normal event

Inadequate managing operations (the gates are operated too late or, anyway, in a wrong way).
Severe floods

4.3 Canals and tunnels

4.3.1 Typical problem

Sand deposition

4.3.2 Original sin

Wrong hydraulic design of the sand traps, if any.

4.3.3 Normal event

Ineffective managing operations (the gates are operated too late or, anyway, in a wrong way).
Severe floods

4.4 Canals

4.4.1 Typical problem

Leakages; stability problems

4.4.2 Original sin

Mistakes in the design or, more often, inadequate materials or techniques in the embankments and drainages execution.

4.4.3 Normal event

Insufficient maintenance

4.5 Tunnels

4.5.1 Typical problem

Leakages; stability problems

4.5.2 Original sin

Incorrect layout with reference to the area geomorphology; inadequate materials or techniques in the execution of the external layer and of the drainages systems

4.5.3 Normal event

Insufficient maintenance of the waterproof layer and of the drainage tools

4.6 Penstock

4.6.1 Typical problem

Landslide: direct damages to the pipes; foundations displacements. (additional stress to the pipes)

4.6.2 Original sin

Incorrect layout with reference to the area geomorphology; mistakes during the excavation activities (increase of the slopes instability)

4.6.3 Normal event

Extraordinary rainfall

4.7 Penstock

4.7.1 Typical problem

Waterhammer in old pipelines

4.7.2 Original sin

Emergency closing devices not completely reliable

4.7.3 Normal event

Insufficient monitoring and maintenance of the emergency closing devices and of the penstock conditions.

4.8 Power station

4.8.1 Typical problem

Differential sliding of the units foundations

4.8.2 Original sin

Insufficient geotechnical works or/and structural rigidity of the units foundations

4.8.3 Normal event

None

4.8 Power station

4.8.1 Typical problem

Inundation from downstream water

4.8.2 Original sin

Wrong power station layout; drainage pumps not reliable

4.8.3 Normal event

Severe floods

4.9 Tailraces

4.9.1 Typical problem

Natural slope sliding; sediment deposition

4.9.2 Original sin

Incorrect slope inclination of the embankments

4.9.3 Normal event

Insufficient maintenance of the slopes

great

5. HOW TO MONITOR THE DEGRADATION OF THE CIVIL WORKS

Typically the plant operators realize that the civil works need some dramatic overhaul when:

1. production lowers, not depending on units efficiency failure;
2. maintenance costs dramatically increase with reference to the usual amount;
3. leakages increase, causing stability risks to the hydraulic works;
4. unusual displacements of the works occur;
5. flood inundation is noticed as a real risk;
6. ....

The monitoring is a consequence of the above mentioned items:

1. routine topographic checks of the dam/weir displacements;
2. constant monitoring and registration of the leakages flow
3. maintenance of the embankments and repairs after the flood events;
4. routine maintenance of the canals and tunnels to prevent the roughness degradation

6. THE CIVIL WORKS REHABILITATION: A CHANCE TO IMPROVE THE PLANT PERFORMANCE

The rehabilitation of the civil works of a hydroelectric plant usually offers a great chance to boost its performance in terms of rated power and energy production.

The correct approach to the rehabilitation takes into consideration these goals:

1. maximum diverted flow rate: an evaluation of the variation needed to the civil works to increase the value of the rated flow of the plant. Very often the old plants have significant margins to improve the river exploitation in a very cheap way;
2. net head: the rehabilitation works can increase the net head, increasing the upstream level, lowering the downstream one or simply reducing the head losses in the waterways;
3. operating hours: a greater reliability of the plant is an usual goal achieved by means of the rehabilitation works, allowing both to reduce the managing costs and to increase the energy production.

Every item can increase the energy production of some percentage, which, all together and adding the improve of efficiency of new generation units, very often reach a double digit amount!

Last but not least, the rehabilitation of old plants involves also the environmental performances, allowing to modernize the civil works to the updated environmental constraints (fish passages, noise reduction, visual impact, pollution risk removal)

6.1 An example: the rehabilitation of the Casnigo SHP

During its life, starting from the beginning of the last century, the Casnigo small hydro plant was upgraded step by step, adding new units, till 5 groups, and adapting the civil works in a “pragmatic” way.

After many years of operation, the plant was very difficult to manage and quite inefficient, making a strong renovation absolutely compulsory and, at the same time, a great chance to improve the plant performances from all points of view: rated flow, net head, operating hours, managing costs, and environmental issues. The table clearly shows the great results achieved by means of the rehabilitation activities.

	Old plant	**Rehabilitated plant**	**%**
Owner	ELETTRA 2000 S.p.A.	=	=
Years	1903	2005	2005
Maximum flow rate	10,0 m^3/s	15,00 m^3/s	+50%
Medium flow rate	7,5 m^3/s	11,12 m^3/s	*+48%*
Net head	9,50 m	12,96 m	*+14%*
Units	5 Francis	1 Kaplan	=
Rated capacity	1.500 kVA	2.100 kVA	+40%
Operating hours	6.550 MWh	8.500	*+30%*
Energy production	4.680 MWh	9.000 MWh	*+92%*
Rehabilitation cost	=	4.628.000 €	=

7. CONCLUSION

Generally speaking, a well designed and built plant doesn't show any problem to the civil works for decades if simple maintenance and monitoring are carried out as routine activities.

But in our experience we observed that many plants have some original sin affecting the civil works in different ways, in terms of efficiency, reliability, maintenance costs and technical life expectation.

In these cases a general overhaul is strongly recommended to solve once forever the main problems of the civil works found out after years of operating experience; and it becomes very often profitable as well if it is implemented in occasion of some general rehabilitation activities involving the electromechanical equipments too.

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Do Small Hydro Power need to be a scaled version of Large Hydro Power?

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1. INTRODUCTION

At first let me state that this by no means will be a scientific paper, this paper express nothing else then some thoughts about the future of Small Hydro Power, and Hydro Power in general, that solely is on the account of the author. Further, more questions will be asked then answers given. Figure 1 shows the traditional layout of a Low Head Hydro Power Plant, and it is mainly the same whether the installed power is 100 MW or 100 kW.

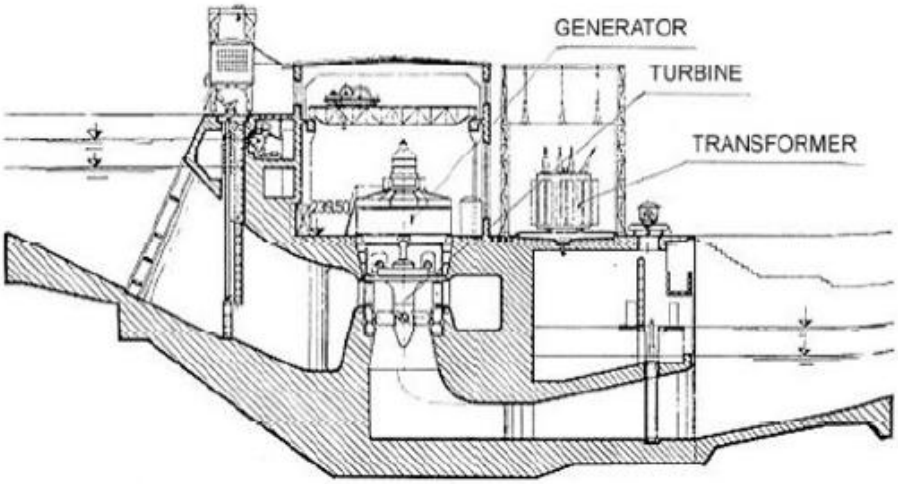

Figure 1 Traditional layout of low head power plant

Figure 2 Oftedal Small Hydro Power Plant (Norway) 2006

Hydro Power has a long tradition, centuries back, and probably the discovery of electricity changed the business more then any other happening through the history. Electricity enabled the transmission of power over relative long distances, with out significant losses compared to the old mechanical transmission system. At the same time it introduced the large power schemes which produced more energy then the local community could consume. However, nothing else has changed much. Oftedal Power Station (3MW) was opened in southern Norway in 2006, and went into the history as another Hydro Power Station with a architectural prize for design. Through history one could sometimes believe that achieving such prizes were the major force for any Hydro Power Development. Engineering pride, instead of engineering creativity has been the case much too often.

Returning to Figure 1 it is easily recognized that all components that together make up the power station, dam, generator, turbine runner, turbine guide vanes, spill gates, other gates, is therefore a purpose. An approach to reforming the structure of a Small Hydro Power plant would obviously be to look on the functionality of each of these components in a framework of a power station that is not dominating the grid, but only supply a fraction of the power that supply the grid. There must be a difference between the specification to be complied with between a power station that deliver 300 MW to the grid, and the power station that supply 1 MW to the grid.

What is the purpose of a Dam in a low head power station placed in or by a river, as illustrated in Figure 3? The answer is rather obvious. It is going to focus the water towards the turbines rather then allowing it to flow down the river. If the topology allows it can also be used to gain Head, and therefore increase the energy output of the power plant. Which factors decide on the dam's construction, again there is an obvious answer to that? The local geology and the water pressure acting on it.

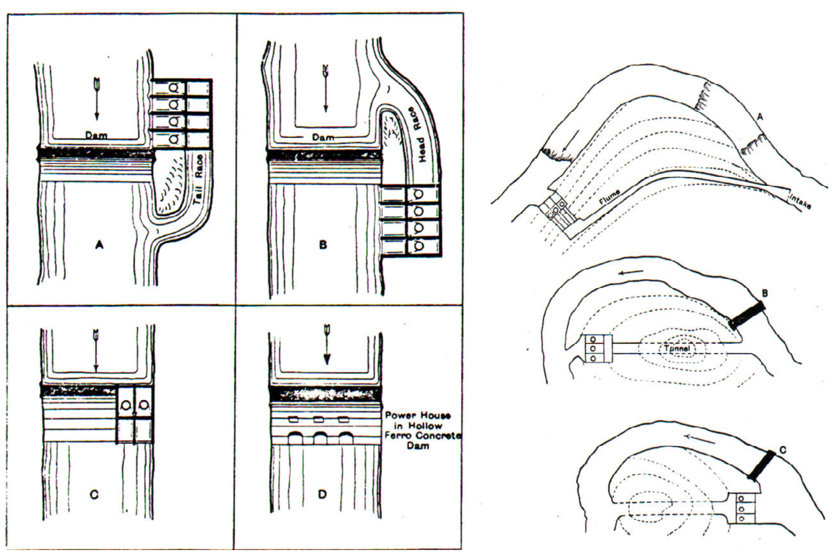

Figure 3 Configuration of Low Head Power Plants

What if there is coming more water down the river then the turbines can swallow? Well there is an obvious answer to that too, the water level behind the dam will increase and eventually flow over the crown of the dam. To have a controlled flow through the dam, that will not harm it spill gates are installed. In large dams where the hydrostatic pressure on this gates are substantial hydraulic operated sector gates made of high quality steel is often installed. On a small dam where the hydrostatic forces are smaller, this can not be necessary. An American company has come up with a smart solution, shown in Figure 4, which combines the dam and spill gates where it is taken benefit from the low hydrostatic pressure in the selection of materials and actuating system. The gates can be placed directly on a concrete foundation (step) an will form the actual dam itself. Compared to the balloons we use in Poland, this system is active and more wear resistant than the balloon is. The system is patented, and shows engineering creativity.

Figure 4 Pneumatic operated Spill Gates forming the dam

Figure 5 Polish Power Plant with Balloon

The wicket gate or guide vanes of a turbine, Figure 6, serve mainly to control the flow into the turbine runner and through that the output of the turbine. In High Head power plants where long penstocks occur they must be carefully controlled so no dangerous pressure transients occur during operation or close down on the turbine. In Low Head power plants this is not a problem and the wicket gate are mainly used to control the turbine output in accordance with the demand in the grid. In a small turbine that produce 1 MW, there normally is not a need to control the output because the produced power at all times will be lower then the minimum consumption in the grid it is connected to. The wicket gate could therefore easily be omitted without any consequences. However, there could be environmental constrictions that make controlling the flow (not output) and in these cases the wicket gate still will be needed. The above argumentation seems quite logical, at least to the author, but still most new Small Hydro Power Plants are equipped with conventional wicket gates, in fact the author only know one manufacturer in White Russia who offers Kaplan turbines without this controlling device. I might very well be wrong on this, but that only underline my continuously need for learning.

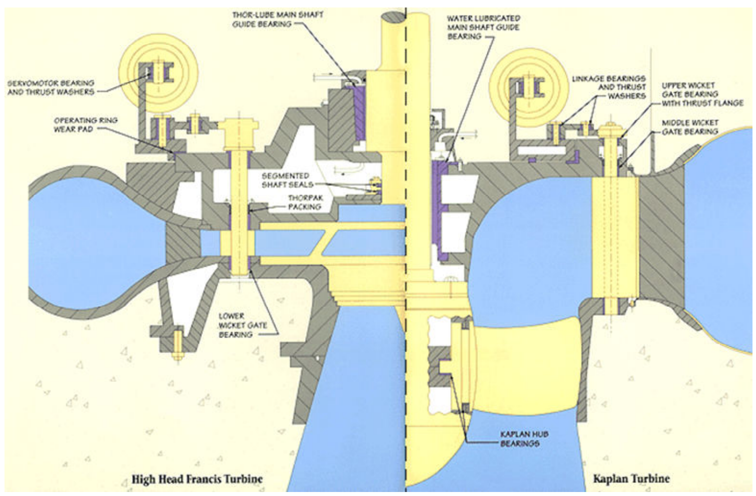

Figure 6 Wicket gate of Kaplan and Francis Turbine

Going around looking at Small hydro Power plants, the author have found that there a substantial amount of them that have quite long open supply channels. They are not only long but they are very nicely made, some of them even have sidewalls made of neatly laid natural stone. The association to Roman aqueducts feels quite in place when admiring the stone work. It is like the owner wants to leave a monument behind, a monument that can be admired a thousand years later like we to day admire the Roman aqueducts and Colosseum in Rome.

- However I see some problems.
- They are expensive
- They collect a lot of trash
- They must be frequently maintained to keep a low flow resistance
- They are a hazard to the public

Figure 7 The author admires the flow through an supply channel for a power plant in the Polish Mountains'

There is an obvious alternative, dig down a plastic pipe. There have to be some digging to make the channel anyway. This way most of the disadvantages listed above will disappear. Not only that the impact on the surrounding nature will be less obvious, and one could even create a park for people to enjoy them self.

Figure 8 Modern Plastic Pipe they come in all sizes

At last let us return to the turbine. Since Edison the Hydro Power business have taken constant speed operation as a law of nature. In relation to classical technology this was most certainly through, the generator had to operate at constant speed in order to maintain a constant frequency. Today, with the developments we have had in electronics this is by far a law anymore. Technically there is no necessity for the turbine to operate at constant speed, electronics fix everything before the energy is supplied to the grid.

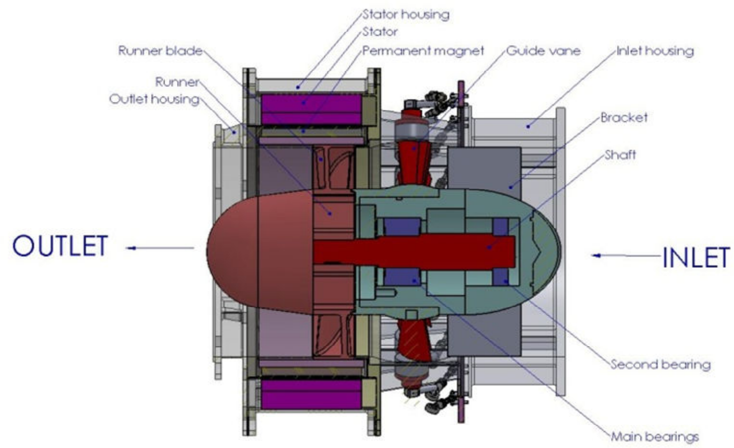

Figure 9 Turbinova integrated variable speed turbine

Figure 9 shows Turbinova's integrated generator and turbine. The turbine is operating at variable speed and equipped with fixed runner blades. Everything is changed, but not really.

It is the author's intention that the discussion above should make creative minds reflecting, not to give answer to the future challenges. I have probably missed essential things, but again that only shows that I as the rest still and always will be on the learning curve.

Small Hydro Action
for Promotion of Efficient Solutions
R&D Actors Network Meeting
The Szewalski Institute of Fluid-Flow Machinery
Gdansk (Poland), September 10-11th, 2009

A Century of Turbine Research without Innovation?

Mads Grahl-Madsen

President, CEDI Sp.zo.o

1. INTRODUCTION

This is a rather provocative title, and clearly the term innovation is essential to the answer of this question. However, the question do not imply a lack of respect for the many brilliant people who has contributed to the development of hydraulic turbines and still contribute substantially to the continuing development of this technology.

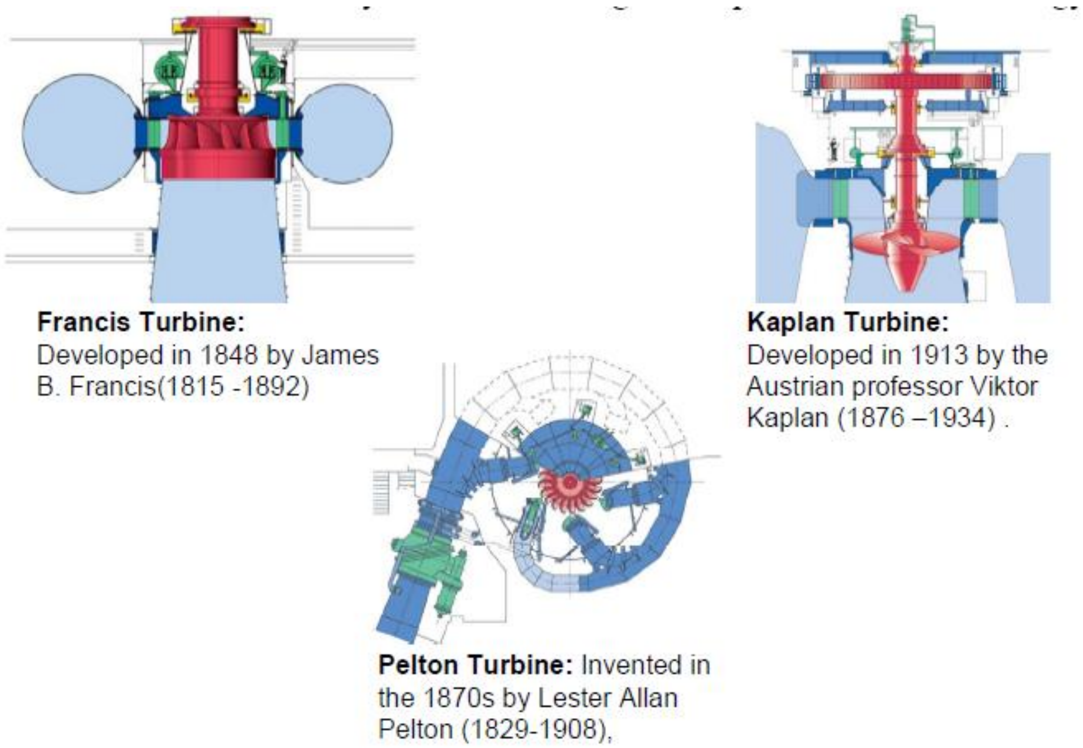

Figure 1 The most commonly used turbine types

If one with the term of innovation means the release of new products that substantially has changed the business, the answer is obviously: Yes, this has been a century without much innovation. As illustrated in Figure 1we still use the same turbines as before and much of the development of them is mainly due to increased material qualities, better machining tools, introduction of digital controllers, etc. The focus from a research and development perspective has mainly been on increased performance and performance prediction. If a wide definition of the term innovation is applied, one that is more in line with the dictionaries, there has been substantial innovation related to analysis and the understanding of their behaviour. But, and there is a “but”, the research and development community have far too often neglected developments from other areas of research that could have been useful, and also to the full extend shown that important discoveries is lost between generations. We have re-invented the wheel many times through the last century.

To comment on all the areas of achievements through a century is not possible, only a few areas of importance both to the designer and the power plant operator will be discussed. For details the reader is referred to the references.

Analysis of turbine flows

The ability of a hydraulic turbine to meet with the specified requirements of generated power, efficiency and stability, are essential to the success of the design. Through all times the possibility of analyse the flow through the turbine therefore has been essential to the practising engineer. A lot of work has been done in this area, in the early years until the 1990's this analysis was based upon the assumption of negligible influence of the fluid viscosity, but since then, thanks to CFD (Computerised Fluid Dynamics) analysis, fully viscous, turbulent and even non stationary models has been applied, Brekke (1996) [6], . However, the early work has not lost is significance to a well designed hydraulic turbine, quite a few of the effects experienced through the operation of hydraulic turbines and the relation of these effects to the design parameters of the turbine can still today only be understood by more simplified analysis then available through the modern computerised design methods.

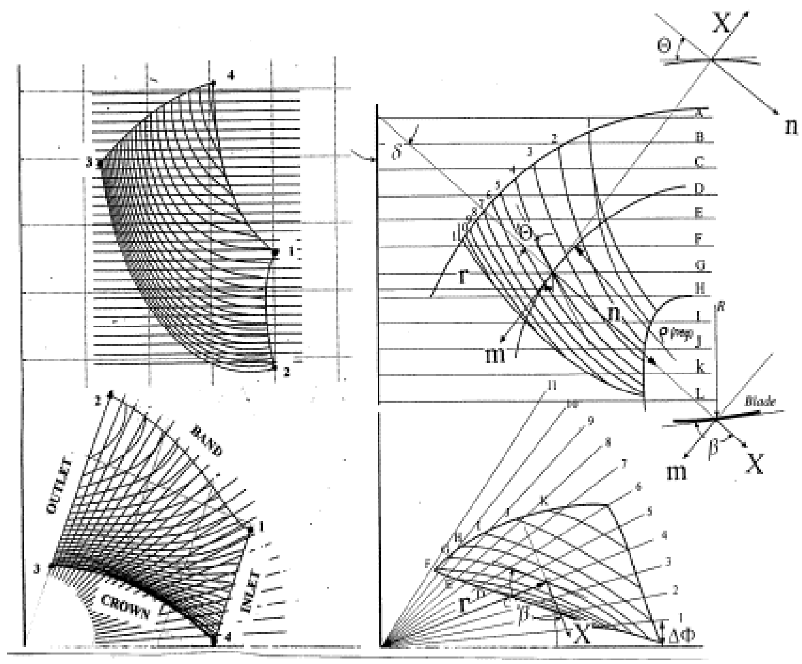

Figure 2 Illustrating the Graphical Solution of the flow through a Francis Turbine Runner

The first comprehensive theoretical treatment of the flow through radial machines was done by Lorenz (1906) [31], and later by Bauersfeld (1912) [3] who applied the theory in Francis Turbines particularly. Dreyfus (1946) [11] published a considerable theoretical work dealing with the internal flow of Francis and propeller turbines, a work that shows a great mathematically capacity, but even today with almost unlimited computer capacity will be hard to carry out on real machines. In Norway Professor Sundby (1937-1938) [35] was a pioneer forming the theoretical basis for the design of Francis turbines, especially turbines with low specific speed. Although his work, assumingly, was heavily influenced by Lorenz (1906) [31], it had a very practical inclination. AS reported by Brekke (1987) [5], this theory is especially valuable in the analysis of the blade design for low specific speed turbines. A general development of this theory can be found in Grahl-Madsen (1985) [15].

Several writers, some of them mentioned above, but also American authors like Csanady (1964) [9] and Wislicenus (1965) [36] wrongly in their theoretical work suggested that the term $d\frac{(u \cdot c_u)}{dn}$ and the term $d\frac{(u \cdot c_u)}{dl}$ between the guide vanes and the runner, both equal zero due to the fact that no torque is transferred prior to the runner inlet edge. u is the peripheral velocity of the runner, c_u the peripheral component of the velocity, n the direction normal to the direction of flow and l the actual direction of the flow. This is due to the flow curvature in this region of the turbine not correct. Only the second of the above terms can be considered equal to zero. As a consequence a lot of turbines where this basis was applied for the mathematical analysis were utilised suffered from major operational problems such as inlet cavitation, the turbines. However, this was not the only reason for operational problems in these turbines but probably a significant contributor taken the nature of some of the problems experienced by these designs.

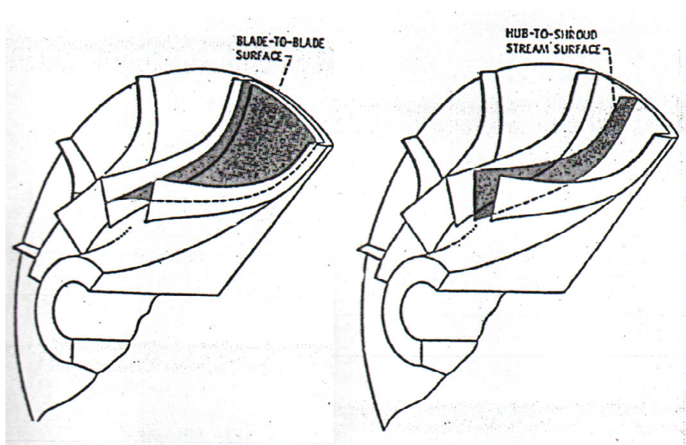

Figure 3 Illustrating Wu (1952) [37] quasi 3D flow surfaces

The Chinese professor Wu (1952) [37] made the most extensive contribution to the theory of turbine flows, and several authors has developed computer algorithms based upon his work. Among these are Hirsch and Warzee (1978) [17], Katsanis and McNally (1969) [22],Hirsch and Warzee (1978) [17], Keck and Haas (1982) [24], Kirsch (1970) [25], Katsanis and McNally (1974) [23], Gjerde (1988) [14] and Chauvin (1977) [8]. The increased capacity of computers changed this quasi 3D approach during the last part of the 1980’s into a focus on the non viscous fully 3D Euler equations, Jacobsen, Billdal et al. (1993) [18], and finally into the development of viscous flow solutions based upon the full Navier Stokes equations, Andersson, Gjerde et al. (1988) [2],Jacobsen, Brekke et al. (1990) [19] and Brekke, Jacobsen et al. (1990) [7].

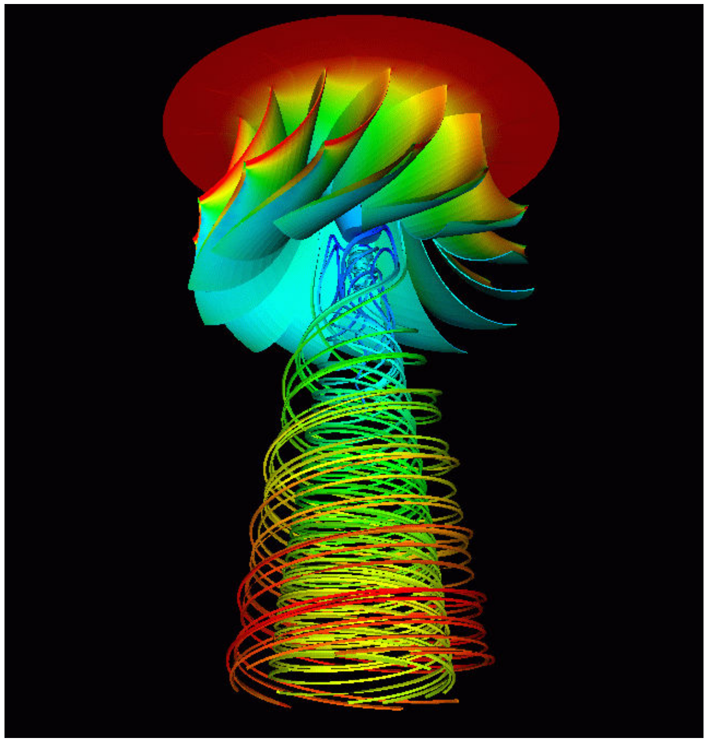

Figure 4 Numerical Results from the GAMM Francis Turbine Runner Davidson: [10]

Real Flow phenomena and their influence on turbine design

Test carried out at the Norwegian University of Science and Technology in the 1960's in order to verify the surface roughness influence on the turbine efficiency showed some interesting results. The test are summarised in Figure 5, and was by no means fully understood at the time.

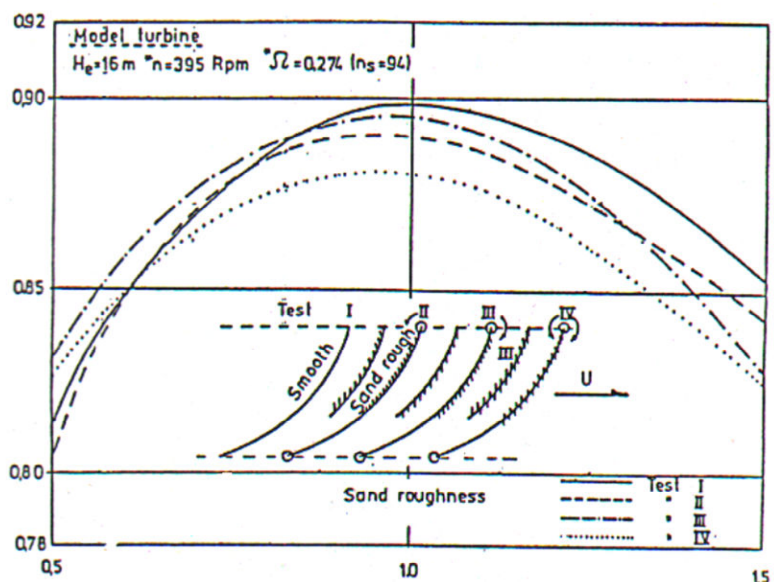

Figure 5 Model turbine tests

In order to understand and their significance to turbine design, both mathematical analysis and extensive research into a variation of sources was necessary, Grahl-Madsen (1985) [16].

The non-dimensional Navier Stokes equation written for the flow through a Turbine Impeller, Grahl-Madsen (1985) [16], can be written as:

$$-\vec{v}\times\left(\nabla\times\vec{v}\right)=-R_o^{-1}\cdot\left(\vec{k}\times\vec{v}\right)-\tfrac{1}{2}\cdot\nabla\cdot\left(1-u\cdot c_u\right)+R_e^{-1}\cdot\nabla^2\cdot\vec{v} \qquad (1.1)$$

And

$$\nabla\cdot\vec{v}=0 \qquad (1.2)$$

The quantities are done non-dimensional by use of the following characteristic expressions:

- $V=\left(2\cdot g\cdot H\right)^{\frac{1}{2}}$ (m/sec)
- D_2 (m)
- $2Y=2\cdot g\cdot H$ (J/kg)

The Rossby Number $R_o=\sqrt{2\cdot g\cdot H}/2\cdot\omega\cdot D$ is a measure of the influence on the flow field from the Coriolis forces, and the Reynolds number $R_e=\sqrt{2\cdot g\cdot H}\cdot D/\nu$ likewise is a measure of influence from viscous forces. The significance of the Rossby number was first (the knowledge of the author) demonstrated in an investigation by Fischer and Thoma (1932) [12]. They visually investigated a centrifugal impeller, and found some very peculiar behaviour. The result of this investigation is shown in Figure 6, where the hatched area indicates separated flow. The speed increase from left to right, while the flow increase vertically. As seen the amount of separated flow along the blades suction side increase with increasing speed and decreasing flow. Separation is also found at overload on the blade pressure side, but it seems to be less dominating then the suction side separation.

Similar results has later been found by a number of other researchers such as Schatzmayr [34], Johnstone, Edge et al. (1991) [21], Lennemann and Howard (1970) [30], Prandtl (1930) [33], Bradshaw (1969) [4; Moore (1973) [32], Furtner and Raabe (1980) [13], and Johnson and Moore (1983) [20].

Figure 6 Flow visualisation in Centrifugal Pump Impeller Fischer and Thoma (1932) [12]

Both Prandtl (1930) [33] and later Prandtl (1930) [33; Bradshaw (1969) [4], found that curvature and Coriolis forces both will influence the turbulent flow by stabilising or destabilising the flow. I the first case the turbulence activity will decrease, while the destabilizing of the flow will increase the turbulence level. As a measure on this effect there can be defined a characteristic number, the Richardson number.

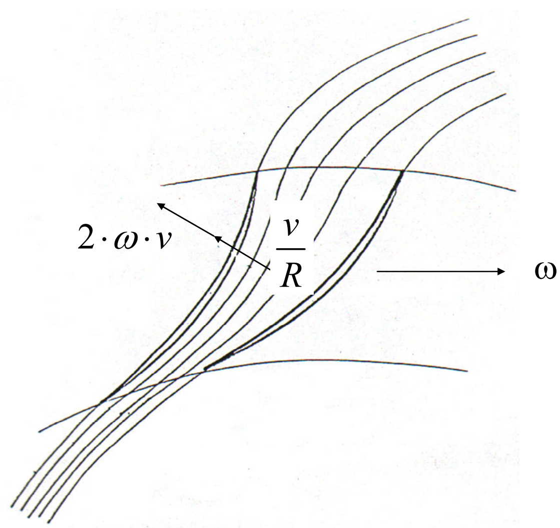

Figure 7 Flow between two turbine blades and the forces acting perpendicular to the flow

$$R_{iC} = \frac{\frac{2}{R^2} \cdot \frac{\partial(c \cdot R)}{\partial n}}{\left(\frac{\partial c}{\partial n}\right)^2} \tag{1.3}$$

And

$$R_{iR} = \frac{-2\cdot\omega\cdot\left(\dfrac{\partial v}{\partial n}+2\cdot\omega\right)}{\left(\dfrac{\partial v}{\partial n}\right)^2} \tag{1.4}$$

If Ri > 0 the flow will stabilise, i.e turbulence will decrease, and with Ri <0 the turbulence will increase due to the destabilisation of the flow. The importance Ri can easily be explained by studying the blade to blade flow of a turbine. AS illustrated in Figure 7 both the effect of the curvature and the Coriolis force will stabilise the flow on the suction side of the blade, while the flow on the pressure side will be destabilised. As a consequence the turbulence will be suppressed on the suction side, while intensified on the pressure side.

Returning to the results from the tests in Figure 5 and assuming that the inlet flow angle at the best efficiency point coincidence with the inlet blade angle several interesting observations can be made. If the blade surface is rough the inner share layer will be disturbed and the local turbulence intensity increases. A rough surface therefore leads to a local flow structure with increased resistance against separation. When the roughness is increased at the blade suction side, the efficiency at the best efficiency point, drop due to increased friction losses. However, at part load when Ro increase the efficiency soon becomes higher then the initial curve where the blade surface is smooth. This is even found when both blade surfaces have an increased roughness. If only the pressure side of the blade is given an increased roughness, there is no change in the part load performance. At overload all results show that the friction losses are dominant.

All these results shows the importance of a focus on details when designing a turbine, and as seen in Figure 5 the effect can be dramatic on the turbine performance. Unfortunately this effect can not be calculated to any accurate quantitative level, but the turbine designer should be well aware of them when designing the turbine.

Performance verification Measurement

Even if the individual location of a turbine, set local operational and performance criteria's, the plant owner should always make sure that the performance of the turbine is in accordance with the specification. For low head turbines, one has to depend on model tests performed in accordance with international standards. On high head turbines, above 100 to 150 meters, an alternative is found in the Thermodynamic method for efficiency measurements, Alming and Vinnogg (1986) [1], Kjölle (1978) [26], Kjölle (1983) [27], Kjölle (1983) [28] and Kjölle (1983) [29]. The principle is shown in Figure 8.

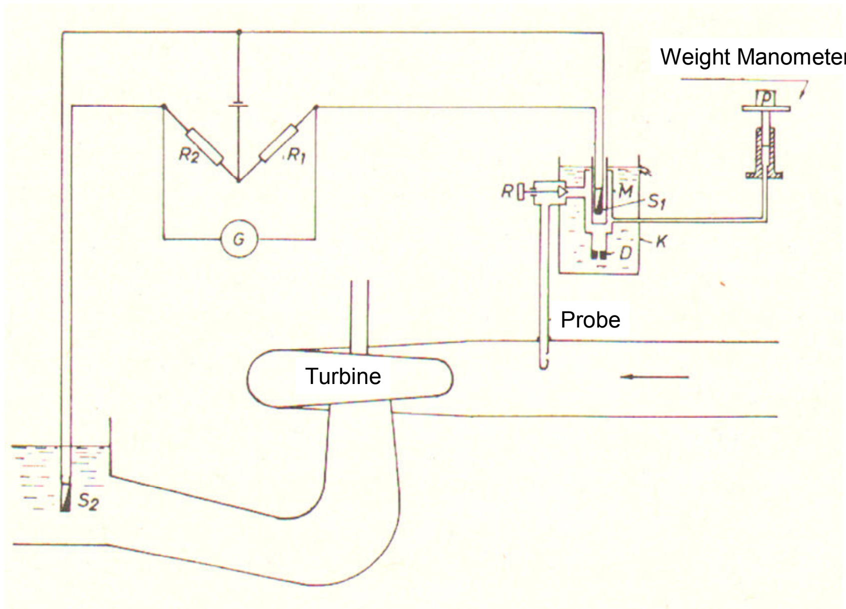

Figure 8 Thermodynamic measurement of turbine efficiency

Conclusion

A lot of good and valuable research has been carried out, but the power plants including the turbines still look like they did 100 years ago. The main research focus has been on optimization of existing turbine solutions, not on innovative new technology.

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[1] Subheading added by the Editor of this volume