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METHOD AND MEANS OF TESTING LOW-HEAD HYDRAULIC TURBINES

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Abstract: *Low-head hydraulic turbines, with maximum powers of 5 kW, exploit at low cost, in pico hydroelectric power plants without dams, flowing water courses with low flows and drops. Determining the optimal constructive variant of such a hydropower unit, which exploits with maximum efficiency a constant water drop, specific to a certain real water course, is done in successive loops of mathematical modeling, numerical simulation and experimental identification. Within these loops, experimental testing of the models is decisive; if this is performed in the laboratory, on dedicated stands, for all models, and the "in-situ" testing is done only for the optimal model, the final costs of achieving the optimal turbine constructive variant are significantly reduced. The article presents a constructive variant for such a stand, which reproduces in the laboratory a real and constant water drop, accompanied by the method of testing the hydraulic turbines, mounted at the upper end of the respective drop. A mixed team from two national research and development institutes, led by the main author of the article, is participating in the creation of this stand, for which a patent application has been filed.*

Keywords: *Low-head hydraulic turbine, optimal model, test stand, test method*

1. Introduction

The most common natural hydrological conditions in low-lying areas, prevalent in Central Europe, are characterized by low flows on small and medium-sized watercourses. Such conditions allow the use of the energy of the head of the water drop by means of water wheels, Banki-Mitchell turbines and propeller turbines [1,2,3].
Small hydraulic turbines, a category that also includes low-head hydraulic turbines, are installed at the head of the water drop, at the level of the upper basin, figure 1-left, while large hydraulic turbines require installation below the water table, at the level of the lower basin, figure 1-right. The water drop, denoted by ***H*** in figure 1, is defined as the distance in meters between the water levels in the two basins.

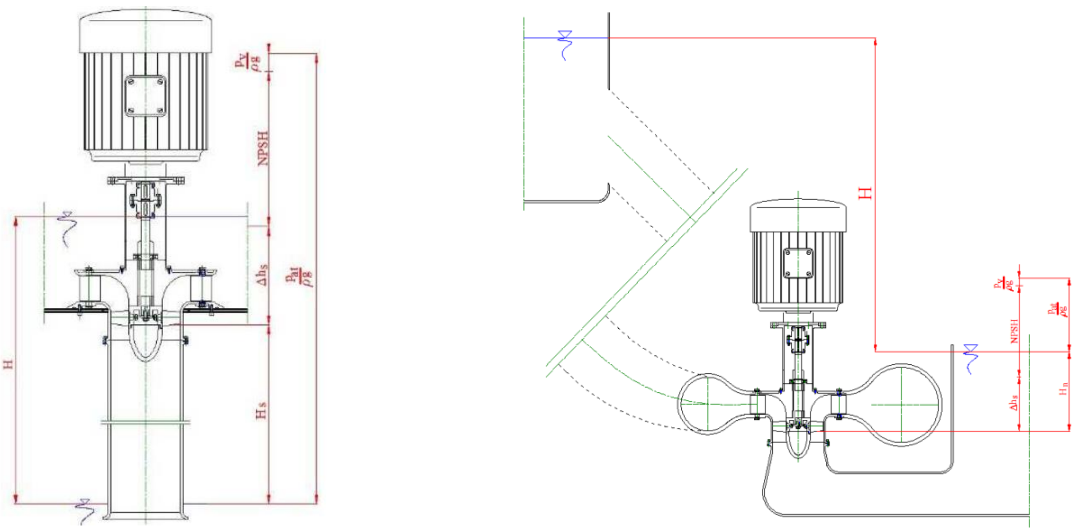


Fig. 1. Installation of hydraulic turbines: left - small turbines; right - large turbines [3]

Mini and pico hydraulic turbines, which operate at a low water drop, of a few meters, have the important advantage that they can work with suction and can be installed at the head of the water drop. This is due to the cavitation reserve of the turbine which, in this case, is much lower than the atmospheric pressure. As a result, a water drop of a few meters allows the turbines to operate practically without an inlet flow, since almost the entire drop takes place in the suction pipe. This construction of the turbine installation significantly reduces the investment cost.

Fig. 2. Installation of low-head hydraulic turbines (at the head of the water drop)

Figure 2 shows the installation of a low-head hydraulic turbine under real operating conditions, with low investment costs, on a small water drop on a river, at the head of the water drop.
Depending on the type of hydraulic energy converted into electrical energy, hydraulic turbines are divided into two categories: *"flow (speed) turbines"*, which harness the kinetic energy, respectively the flow rate $\boldsymbol{Q}$ [m^3/s] or the speed $\boldsymbol{v}$ [m/s] of the water and "*drop turbines*", which exploit the potential energy, respectively the drop $\boldsymbol{H}$ [m] of the water. Therefore, the experimental test stands for hydraulic turbines will be "flow (velocity) stands", with larger horizontal dimensions and "drop stands", with larger vertical dimensions.
A constructive solution for a “drop stand” is presented below, original in the way of achieving a prescribed constant drop $\boldsymbol{H_p}$, [4]. This drop can be adjusted in a range with a length proportional to the vertical dimension of the stand.

2. Vertical stand for testing low-head hydraulic turbines

This stand makes more energy efficient the operation of a constant-level tank [5], located at a height and permanently supplied with an inflow flow rate greater than the useful flow rate (effluent), $\boldsymbol{Q_u}$, required by the consumer (the tested turbine), the excess flow rate $\boldsymbol{Q_e}$ being discharged into a second basin, located on the ground, from where it is taken over by a pumping group with a constant flow rate.
The energy efficiency of the constant-level tank is achieved by automatically regulating the flow rate of a pumping group, $\boldsymbol{Q_p}$, consisting of three adjustable pumps, coupled in parallel. The pumping group sucks from a lower tank, located on the ground and discharges into an upper tank, located at a height and which communicates through a vertical pipe with the first, so that $\boldsymbol{Q_e = Q_p - Q_u = 0}$, and the drop $\boldsymbol{H}$, defined as the distance between the water levels in the two superimposed tanks, remains constant [6].

2.1 Constructive-functional scheme of low-head hydraulic turbine test stand

The construction-functional scheme of the stand in Figure 3 contains the following subassemblies:
1- **adjustable flow pumping group**, consisting of three adjustable centrifugal pumps (**1.1, 1.2, 1.3**), connected in parallel to sum the flow rates, each driven in rotational motion by a 380 V electric motor, equipped with a frequency converter for rotational speed regulation. Each pump, separated from the

suction/discharge manifolds of the group with isolation valves (a check valve is also mounted before the discharge valve) sucks, through the pipe **1.4** from the lower tank and discharges, through the pipe **1.5**, into the upper tank. Elastic sleeves are mounted between these pipes and tanks, which stop the propagation of vibrations of the pumping group to the tanks. For any excess flow, occurring in the event of a possible failure of the automatic flow rate regulation system, the overflow pipe **1.6** was provided.

2-lower tank, equipped with: the partition wall **2.1**, separating the suction and discharge compartments of the pumping group; the cover **2.2** equipped with atmospheric contact; the level glass **2.3**, for viewing the water level;

3-upper tank, equipped with: the spillway threshold **3.1**, which separates the compartment connected to the discharge pipe, from the compartment connected to a transparent tube, through which the water flows into the lower tank; the cover **3.2** equipped with atmospheric contact; the level glass **3.3**, for viewing the water level;

4-vertical and submerged pipe, formed by a transparent plexiglass tube **4.1**, equipped with the flange and gasket **4.2**, above which the model of the low-head turbine to be tested is mounted;

5-model of the low-head turbine to be tested, formed by the stator **5.1** and the rotor **5.2**;

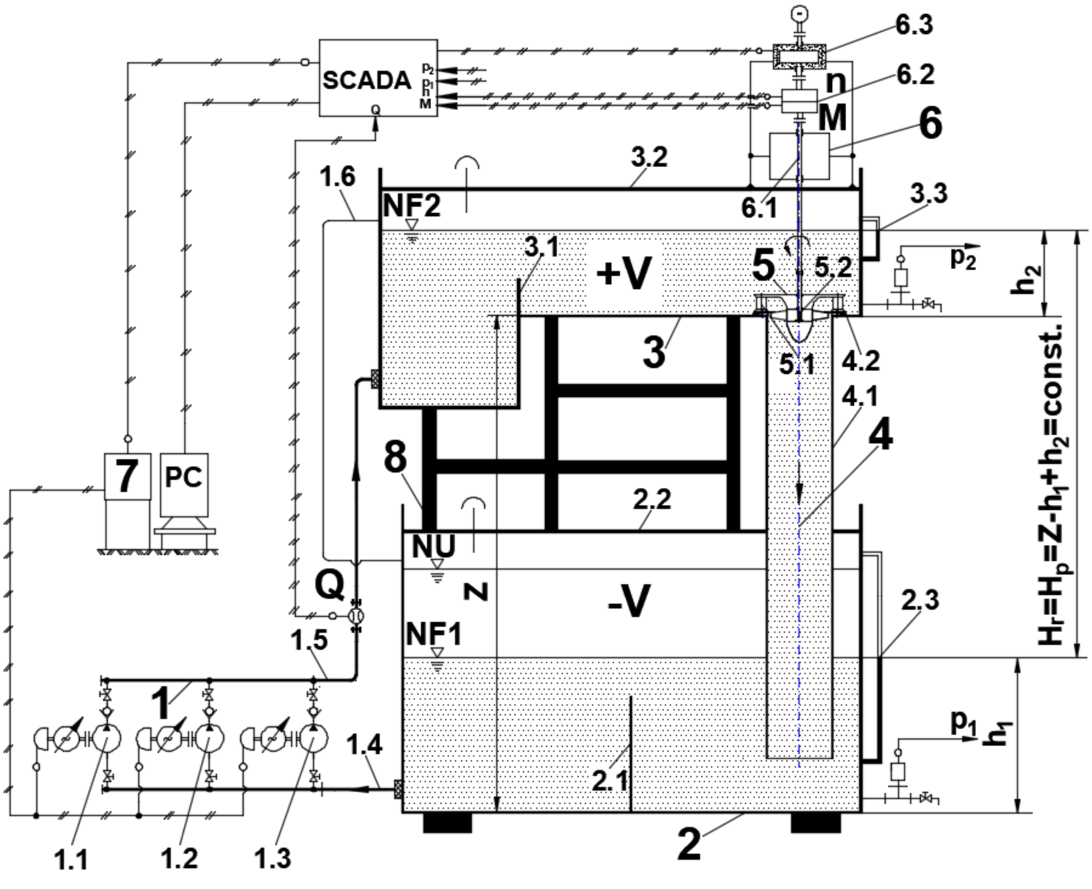


Fig. 3. Constructive-functional scheme of low-head hydraulic turbine test stand

6-adjustable braking system, which is coupled to the turbine shaft and consists of: shaft **6.1**, with two radial-axial bearings; torque and rotational speed transducer **6.2**; magnetic powder brake **6.3**, with adjustable resistive torque depending on the supply current; a 24 V DC electric motor, necessary to drive the brake before starting the tests on the stand, for homogenizing the magnetic powder and determining the value of the friction torque in the bearings;

7-electrical panel for powering the motors of the pumping group and the SCADA system;

8-metal support for the two tanks, equipped with verticality adjustment screws.

The stand is equipped with the following four transducers, respectively: ***p_1*, *p_2* - hydrostatic pressure transducers**, mounted at the base of the tanks (between the tank and the drain valve), which indirectly measure the water levels in the two tanks:

$$\boldsymbol{h_1 = \frac{p_1}{\rho \cdot g}} \;;\; \boldsymbol{h_2 = \frac{p_2}{\rho \cdot g}}, \tag{1}$$

in which: *$[\rho] = 1000\ Kg/m^3$, $[g] = 9{,}81\ m/s^2$, $[p_1, p_2] = N/m^2$, $[h_1, h_2] = m$*

Q-flow transducer, which is mounted on the **1.5** pipe and measures the flow rate of the pumping group;
M, n-torque and rotational speed transducer, which measures the mechanical parameters of the tested turbine.
The SCADA system of the stand, equipped with a power supply, programmable automation PLC, the four transducers and the magnetic powder brake ensures monitoring of the parameters of the tested turbine, automatic control of the stand and experimental data acquisition.

2.2 The operating principle of the stand

The stand circulates, in a closed circuit, a volume of water between two vertically superimposed tanks; between the lower tank and upper tank the water is forcibly circulated by pumping, and in the opposite direction, the water flows by gravity through the transparent circular tube, at the end of which the tested hydraulic turbine is mounted.

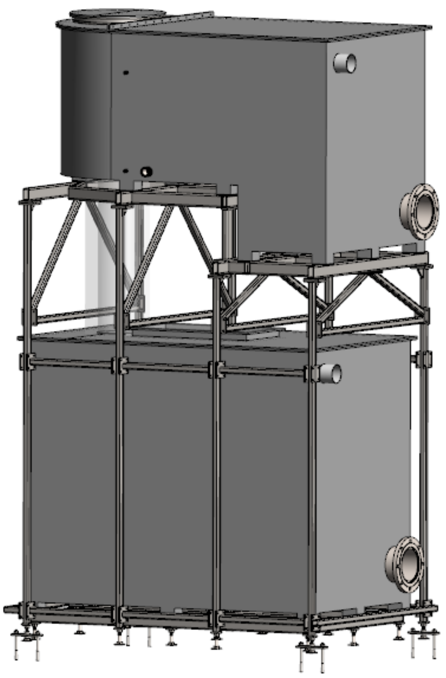


Fig. 4. Subassembly of overlapped tanks

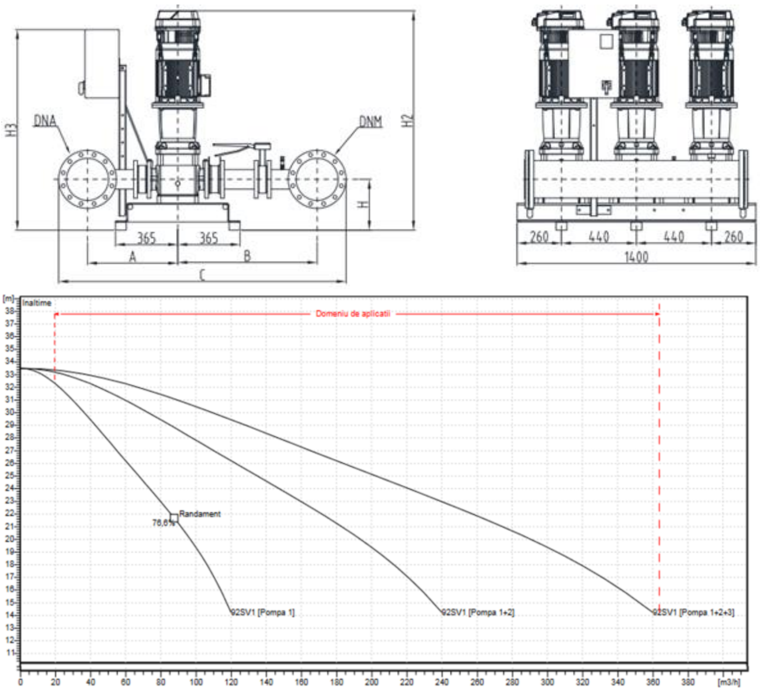


Fig. 5. Pumping group with adjustable flow (3 centrifugal electric pumps model 92SV1N075T-LOWARA)

Before putting the stand into operation, the lower tank is filled with clean water up to the filling level **NU** (Fig.3). Then, the pumping drop that the pumping group ***H_r*** must achieve, at which the experimental tests will be performed, is prescribed from the SCADA programmable controller.
+V, -V represent the volume of water sucked (-V) by pumping, from the lower tank, respectively the volume of water discharged (+V) by pumping, into the upper tank, to achieve the water drop ***H_r***.

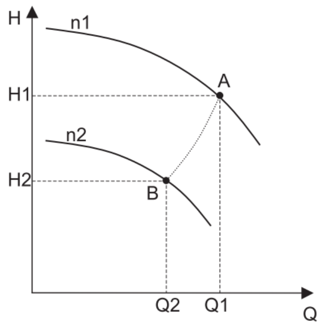
The SCADA system, in connection with the transducers p_1 and p_2 (which measure the water levels in the tanks h_1 and h_2), will automatically adjust the flow rate of the pumping group (by modifying the driving rotational speed of the three pumps) so that:

- the forcibly circulated flow rate, by pumping, Q_p, is equal to the useful flow rate, Q_u, necessary for the tests, which flows by gravity;
- after equalizing the flows and achieving the drop H_r, the flow value Q_p should be kept constant.

The equation that highlights the automatic flow regulation for a given reference pumping head is:

$$H_r = H_p = Z - h_1 + h_2 = const. \tag{2}$$

where Z is the distance in meters between the two pressure transducers, mounted in proximity of the bottoms of the overlapping tanks.



$n_1 > n_2$

n_1 = initial rotational speed; Q_1 = initial flow rate;
H_1 = initial drop; P_1 = initial power;

n_2 = necessary rotational speed; Q_2= necessary flow rate;
H_2 = necessary drop; P_2 = necessary power.

Fig. 6. Modification of pump parameters (Q, H, P) by varying its drive rotational speed

The installation of the frequency converter on each of the three pumps makes it possible to vary their drive rotational speed. The variations of pump rotational speed, figure 6, have the effect of modifying the flow rates Q, the drops H and the powers P according to the following equivalence relations:

$$\frac{Q_1}{Q_2} = \frac{n_1}{n_2}\ ;\ \frac{H_1}{H_2} = \left(\frac{n_1}{n_2}\right)^2\ ;\ \frac{P_1}{P_2} = \left(\frac{n_1}{n_2}\right)^3 \tag{3}$$

2.3 The main functional characteristics of the stand

Overall dimensions (height x width x length): *4.2 m x 1.5 m x 3 m*;
Volume of the tanks: lower tank *V = 3840 l*; upper tank *V = 2400 l*;
Adjustment range of the water drop (distance between the water levels in the tanks): *H = 2.2-2.4 m*;
Types of low-head hydraulic turbines that can be tested: *Vortex, helical, etc.*;
Measurements and tests that can be performed: *flow rate and pressure* in the turbine suction; *torque* and *rotational speed* at the turbine shaft; stationary curves of *variation of torque and rotational speed* at the turbine shaft, *function of load and flow rate*;
Inner diameter of the vertical transparent plexiglass pipe: $Ø_i$ *= 230 mm*;
Pumping group consisting of 3 pumps connected in parallel: flow rate *Q = 100 l/s* at load *H = 2.4 m*;
Electric motor with frequency converter for pump drive (3 pcs.): power / supply voltage / frequency / rotational speed = *7.5 kW / 3x380-415 V / 50Hz / 2900 rpm*;
Nominal diameter of suction / discharge pipe: *DN 200 mm*;
Overflow pipe diameter: *110 x 3.2 mm*;
Outer diameter of the turbine rotor tested on the stand: $Ø_e$ *= 228 mm*;

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Measuring range of the transducers: flow rate transducer $Q = 34\text{-}1131\ m^3/h$; static pressure transducer $p = 0\text{-}0.25\ bar$; torque and rotational speed transducer: $M = 0\text{-}20\ Nm$; $n_{max} = 3000\ rpm$; **Magnetic powder brake**: torque $M = 0\text{-}35\ Nm$; rotational speed $n = 60\text{-}3000\ rpm$.

3. The method testing low-head hydraulic turbines

The method of testing low-head hydraulic turbines, on the stand in Fig. 3, contains two types of operations: *stand preparation operations* for experimental testing; *determination of the functional characteristics* of the tested turbine model.

3.1 Stand preparation operations

Check the verticality of the two overlapping tanks as a whole. The verticality of the overlapping tanks will be checked and restored, if it is necessary (by operating the adjustment screws on the tanks support).

Filling the stand with water, adjusting the water level, pumps aeration, mounting the turbine and braking system. The lower tank will be filled, with clean and filtered water from the mains, until the water reaches the filling level **NU**, visualized on the level indicator **2.3**. This level is calculated so that the volume of water from the tank to ensure the filling of the pumping circuit consisting of: suction pipe + pumping group + discharge pipe + upper tank maximum level + transparent vertical pipe***;*** If it is necessary, the drain valve near the transducer $\mathbf{p_1}$ is also used to adjust the filling level. The pumps aeration is done by unscrewing / tightening of the vent caps of each pump. On the flange of the transparent tube, the model **5** of the turbine to be tested will be mounted, to which the adjustable braking system **6** will be connected.

Prescribed drop value $H_r = H_p$, defined by equation (2).

Start the pumping group and initiate the flow adjustment program. The operation will be performed in two steps:

***step 1*:** the pumps of the group are started, at ½ of the nominal rotational speed, to fill the hydraulic circuit and the upper tank up to the level of the overflow threshold **3.1**, which separates the tank into two compartments;

step 2*:* when the water reaches the level of the spillway threshold **3.1** and flows by gravity through the transparent tube into the lower tank, the program compares, by analyzing the water levels in the tanks, the flow rate Q_s of the flow through the vertical transparent tube, which depends on the shape of the tested turbine and the vortex formed at the turbine outlet, with the flow rate Q_p of the pumping group. Two situations can occur:

2.1 if $Q_s>Q_p$, because in the upper tank the water stagnates at the level of the spillway threshold for a calculated time interval, in which the hydrostatic pressure transducer p_2 does not transmit information of the level increase in the upper tank**,** the **SCADA** system commands the automatic increase of the flow of the pumping group, by increasing the drive rotational speed of the pumps, until the achieved drop H_r equals the prescribed drop H_p. From that moment, when the operating levels **NF1** and **NF2** are stabilized in the two tanks, and a volume **V** of water is transferred by pumping from the lower tank **-V** to the upper tank **+V,** the **SCADA** system will provide a closed-loop adjustment of the rotational speed of the pumps, implicitly of the influent flow to the upper reservoir, for the constant maintenance of the drop $H_r=H_p=Z-h_1+h_2$, implicitly of the effluent flow to the upper reservoir;

2.2 *if* $Q_s<Q_p$, the **SCADA** system commands the automatic reduction of the pumps rotational speed, and upon receiving the prescribed value of the drop H_p, the system acts to keep it constant, implicitly the effluent flow to the upper tank.

3.2 Determination of functional characteristics of tested turbine model

On the stand, two mechanical parameters (torque M and rotational speed n) and two hydraulic parameters (drop H and flow rate Q) can be measured. With the measured parameters, three types of functional characteristics of the turbine model installed on the stand can be determined, namely:

characteristic $M = f(Q)$ at $M_r = const.$, respectively the moment at the turbine axis as a function of flow at constant load (the same supply current of the magnetic powder brake) determined experimentally for several constant drops H;
characteristic $n = f(Q)$ at $M_r = const.$, respectively the rotational speed at the turbine shaft as a function of flow at constant load, determined experimentally for several constant drops H;
characteristic $n = f(M_r)$ at $Q = const.$, respectively the rotational speed as a function of load at constant flow rate, determined experimentally for several constant flow rates Q.

4. Conclusions

- The presented stand is intended for testing low-head axial hydraulic turbines with a vertical shaft; these turbines are mounted at the head of the water drop.
- The stand is supplied by a height tank with a constant level, for which the inflow flow, respectively the supply flow of the stand, is equal to the effluent flow, respectively the useful flow of the stand for low-head hydraulic turbine tests.
- The stand regulates the water drop in the vertical section of the turbine test and maintains the adjusted value constant during the experimental tests.
- The water drop from permanent watercourses is simulated in a transparent vertical pipe, made of Plexiglass, supplied by a constant level tank.
- The stand allows the determination of the following functional characteristics of the tested hydraulic turbine: characteristic $M = f(Q)$ at $M_r = const.$, respectively the moment at the turbine shaft as a function of flow at constant load, which can be determined experimentally for several constant drops H; characteristic $n = f(Q)$ at $M_r = const.$, respectively the rotational speed at the turbine shaft, as a function of flow at constant load, which can be determined experimentally for several constant drops H; characteristic $n = f(M_r)$ at $Q = const.$, respectively the rotational speed as a function of load at constant flow, which can be determined experimentally for several constant flow rates Q.

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