DETERMINATION OF TURBINE EFFICIENCY FOR SMALL HYDRO POWER PLANTS

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Abstract - In this paper, authors briefly present the methods for determining the efficiency/performance of a hydraulic turbine, as well as the purpose, the necessity of applying *in situ* determination methods of the efficiency of hydraulic turbines from a hydropower plant. These efficiency tests are an essential practice to ensure that the performance of the hydraulic turbine and the hydropower plant have not degraded to unacceptable levels. Also in this paper are presented the results of the efficiency tests carried out at a cascade of three hydropower plants from the arrangement of Râul Mare downstream.

Keywords: discharge, turbine efficiency, hydraulic turbine, hydro-unit.

1. INTRODUCTION

We can consider that performance testing of hydropower plants facilities is a vital, yet challenging activity. It is important because, without testing, assessment of how well a facility is performing – vis-à-vis how well it possibly could perform – is, at best, a difficult task [1].

Also performance testing is an essential practice to ensure that hydropower plant performance has not degraded to unacceptable levels. Moreover, testing is needed as a part of programs to improve the efficiency, output and economic performance of single hydropower plant or multiple plants that operate in a coordinated manner. Optimization has been an important focus in last years. Optimization typically requires performance testing in order to verify the performance of units and facilities and to establish benchmarks.

Another important reason for performance testing has to do with the procurement of new turbines or runners and new pumps or impellers, or in contracting for the rehabilitation of such equipment. Specifically, performance testing is often necessary for verifying contractual guarantees.

Usually, a test code such as IEC 41 [2], respectively SR EN 60041[3] is used, in compliance with conditions for achieving measurements provided in ISO 3354 [4]. Internationally, lately, more and more performance tests for hydraulic turbines are performed in accordance with the provisions of the IEC 62006 international standard [5] and the American Society of Mechanical Engineers' Performance Test Code for Hydraulic Turbines and Pump Turbines ASME PTC-18 [6]. Few of Romania's hydropower plants have excess water that would justify capacity increases. The majority of reclamation's turbine runner replacement contracts focus on efficiency improvements aimed at reducing the amount of water for each megawatt-hour generated.

Efficiency and maximal power output are two of the most important goals to analyze in hydraulic turbines.

Hydraulic turbines normally operate in variable head conditions; therefore, tests to analyze performance are frequently realized for a selected number of hydropower plant heads.

Usually it is limited to three heads: low, medium and high. The efficiency of hydraulic turbines is most frequently expressed using the weighted average efficiency or arithmetic mean efficiency, calculated from the measured results in the examined heads. To perform the calculation of efficiency is necessary to know several parameters such as kinetic and potential energy of water due to the position, because of this is required to know the discharge entering the turbine. The discharge of water through the turbine (Q) is determined by the volume of water flowing in time unit. The measurement of this quantity is one of most difficult tasks in hydraulic turbine tests.

2. METHODS FOR DETERMINING THE EFFICIENCY OF HYDRAULIC TURBINES

Determining hydraulic turbine efficiency.

Hydraulic turbine efficiency determining includes absolute efficiency measurement methods and relative efficiency measurement methods. Absolute efficiency measurement includes direct and indirect measurement.

Absolute efficiency direct measurement method

A representative absolute efficiency measurement method is the thermodynamic method. The method's principle is the law of conservation and transformation of energy (the first law of thermodynamics). Hydraulic loss will come into being while water passes through the passageway of the hydraulic turbine, and the hydraulic loss will convert into thermal energy. And that will results in temperature difference between the inlet and the outlet of hydraulic turbine. Efficiency can be calculated by the parameters, such as temperature, pressure, velocity, elevation and the shaft power measured at specified section and location of spiral case and draft tube.

Absolute efficiency indirect measurement method

The steps of the absolute efficiency indirect measurement method are as following. Firstly, the discharge, water head and power should be measured. Secondly, the efficiency will be calculated by the mentioned parameters. The main difficulty and key problem is the absolute turbine discharge measurement. The recommend absolute discharge measurement methods in IEC 41 are current-meter method, pilot tubes, pressure-time method, tracer methods, weirs etc. But for huge hydropower units, available absolute discharge methods are limited because their pipe diameter is so large and the water head is very high.

As for current-meter method, because of the influence of the mounting bracket and current meters on the flow regime, measurement precision will decreases absolutely. Furthermore, it is difficult to install the hydraulic frame before the runner of large diameter, high water head hydraulic turbines. The installation of the frame can bring risk for the safety operation of the turbines.

Pressure-time method [7] is suitable for the shut down operating condition of turbine, and is not suitable for the discharge measurement under normal operating condition. For huge turbines, the discharge maybe reach 350 [m^3/s], tracer methods are also not available in engineering application.

From the view of present technology and engineering application, it is viable to use ultrasonic flow meter to measure the absolute large-caliber turbine discharge. For a long time, the key problem for ultrasonic flow meter is the on-site calibration. Scientists and researchers have done many effective scientific research and practical works, including the influence of the factors such as probe installation, geometric parameters and integration methods on the accuracy of the ultrasonic flow meter [8], [9]. So, we can increase the accuracy of the ultrasonic flow meter and its sensitivity can meet the command of the turbine absolute efficiency test.

Relative efficiency measurement method

Turbine relative efficiency is measured by differential pressure devices [10]. The principle of differential pressure methods is as following. When water with a certain velocity passes through spiral case, centrifugal force will be produced because of the bend of the center line spiral case. Differential pressure, Δh, will come into being between the inner side and outside of the spiral case. Based on Bernoulli equation, the discharge Q is determined according to IEC41. This method is called Winter-Kennedy method.

The Winter-Kennedy method was initially described by Ireal A. Winter and A. M. Kennedy in their paper [11]. IEC 41 considers this as a relative method and can be used only as a part of field acceptance test if the method is calibrated by absolute method considered in the standard. The standard also suggests that Winter-Kennedy method cannot be used to check the guarantee power of the machine unless both parties agree.

Winter-Kennedy method in case Kaplan turbines, Francis turbines and the differential pressure method in bulb turbines have similar theoretical foundations. In all cases, the discharge is dependent on the measured pressure difference between two corresponding points located in flow system according to the formula:

$$Q = k(\Delta h)^n \tag{1}$$

where, Q is discharge, Δh is pressure difference on taps of spiral case, k is the constant coefficient, experimentally determined from calibration, while n is power exponent, theoretically equal to 0.5.

The Winter-Kennedy method utilizes the static pressure difference between the outer ($p1$) and inner side ($p2$) of the turbine spiral case due to the centrifugal force that is acting on the curved streams of liquid in the spiral case ($\Delta h = p1 - p2$). The possible location of the pressure taps is presented in Fig. 1a according to IEC 41 Standard for a concrete half-spiral chamber of classic Kaplan turbine. A sample distribution of pressure taps of the differential pressure method in the case of flow system of the hydro-units with Francis turbines is shown in Fig. 1b, and with a bulb turbines (without a spiral) is shown in Fig. 1c.

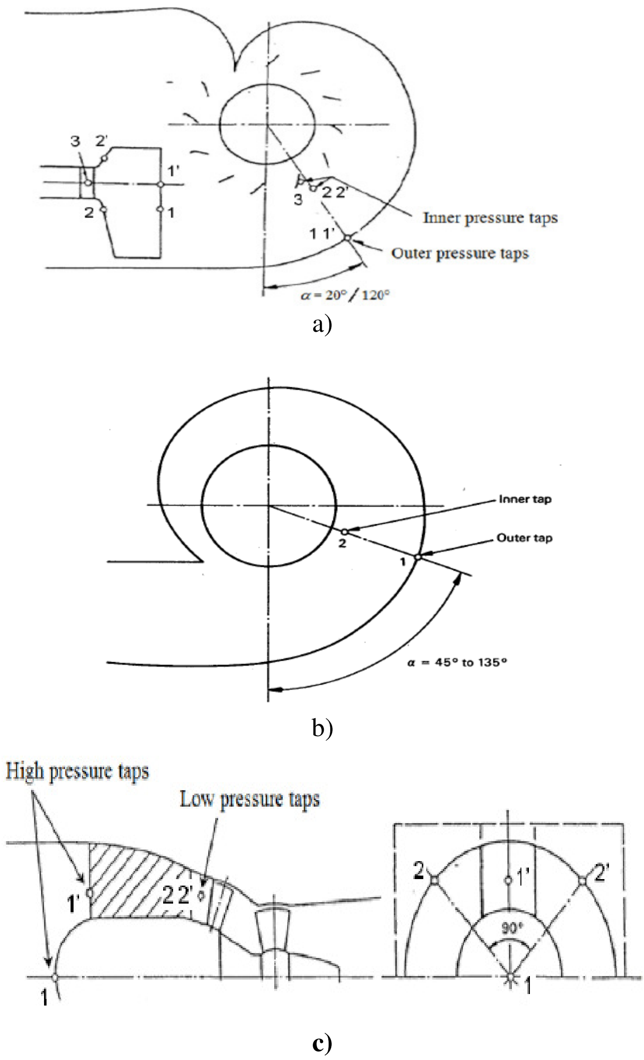


Fig. 1. Location of differential pressure taps in: (a) Kaplan turbine equipped with a concrete half-spiral chamber; (b) Francis turbine; and (c) bulb turbine [1]

In all three cases, after their calibration using one of the primary methods (e.g., current-meter method) and determination of the K and n constants can be used to measure the absolute value of the discharge through the turbine. In order to secure the highest possible correctness of the results obtained using these methods, the pressure difference should be measured using a high-accuracy transducer. Then, we can expect that the accuracy of measurements using the differential pressure method will be close to that of the method used for calibration.

Methods for determining the discharge based on the measurement of differential pressure, due to their characteristics, are recommended to use during optimization tests of the double-regulated turbines for measuring the relative discharge through the turbine. In order to obtain the correct result using these methods, it is important to construct the measurement systems properly (precise location of pressure taps, tightness of the measuring system and easy access to the equipment) and to use suitable measuring equipment (differential pressure transducer of high class).

3. DETERMINING THE EFFICIENCY OF HYDRAULIC TURBINES FOR THREE HYDROPOWER PLANTS IN CASCADE

Knowing the technical condition of the installations in the hydropower plants based on *in situ* tests constitutes one of the means without any realistic policy regarding the operation, maintenance and refurbishment of the equipment cannot be conceived.

In order to substantiate some measures regarding the exploitation, maintenance and/or refurbishment of hydro units, *in situ* energy performance tests are used more and more frequently.

In order to exemplify the efficiency tests at hydropower plants, it was chosen a cascade of three hydropower plants from Păclişa lake sector - the escape channel HPP Toteşti II from the arrangement of Râul Mare downstream [12].

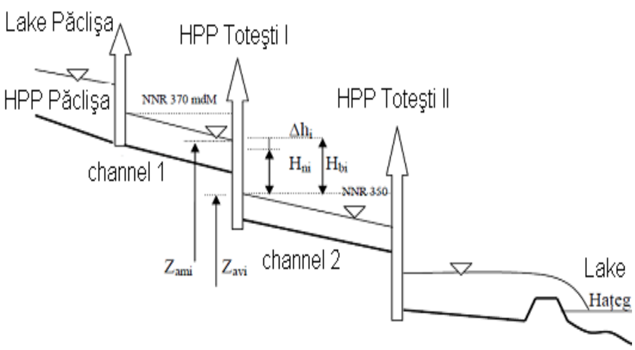


Fig. 2. The scheme of Păclişa lake sector - HPP Toteşti II escape channel

Păclişa accumulation lake has a relatively modest useful volume (about 5.6 million cubic meters), which is reduced to less than 4 million cubic meters by restrictions imposed on the maximum allowed level in accumulation (maximum 388.5 [mdM], compared to the project NNR of 390 [mdM]), as a result of excessive infiltration through dams.

Păclişa hydropower plant with reservoir and two hydropower plants downstream, Toteşti I and Toteşti II, which are placed on derivation channels, have the design characteristics (installed power, installed discharge, gross head, net head) and two Kaplan type KVB 8.4-21 turbines each.

To determine the efficiency of the turbines, respectively, the hydro-units, the discharge was measured using the current-meter method. According to the standards in force ([2], [3], [6]) the current meter method is the only recommended method for determining the absolute discharge of a hydraulic turbine that equips a low head hydropower plant.

The current-meter method aims to determine the velocity distribution in a cross section of the water stream in order to determine the discharge to be measured. The test is expeditious, it is applicable to clean enough water so that dissolved or suspended particles do not affect the accuracy of the measurements.

In order to determine the discharge, respectively, the calculation of the turbine efficiency of Paclişa, Toteşti I and Toteşti II hydropower plants, a hydrometric frame was used on which were placed current meters.

The number of measurement points for the measurement section was established according to IEC 41 standard using the formula:

$$24\sqrt[3]{A} < Z < 36\sqrt[3]{A} \qquad (2)$$

Z is the number of measurement points and A is the area of the measurement section.

Fig. 3. Hydraulic frame used to place the current meter

Hydraulic power P_H

Hydraulic energy resulted from the product of discharge, head, density and gravity.

$$P_H = \rho \cdot g \cdot H \cdot Q \qquad (3)$$

Hydro unit efficiency η_{T+G}

The efficiency of the HA hydro unit was calculated by dividing the active power of the generator by the hydraulic power.

$$\eta_{T+G} = \frac{P_G}{P_H} \tag{4}$$

Turbine efficiency η_T

The efficiency of the turbine was calculated by dividing the efficiency of the hydro unit with the efficiency of the generator (assumed).

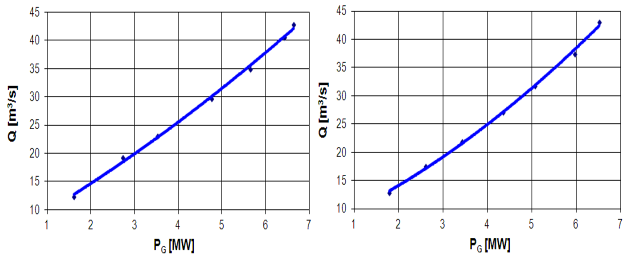
$$\eta_T = \frac{\eta_{T+G}}{\eta_G} \tag{5}$$

and:

$$P_T = \frac{P_G}{\eta_G} \tag{6}$$

where: g is gravitational acceleration, ρ - water density, H - represents head and, respectively, P_G is generator power, P_T is turbine power

Following *in situ* measurements of these three hydro power plants in analyzed sector, the following consumption characteristics were obtained (Q represents the discharge according to the power at P_G generator terminals).



a) b)

Fig. 4. Characteristics of consumption for HHP Păcliaşa HA1 (a) and HA2 (b)

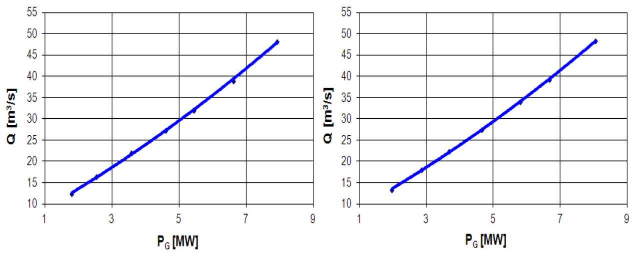


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Fig. 5. Characteristics of consumption for HPP Toteşti I HA1 (a) and HA2 (b)

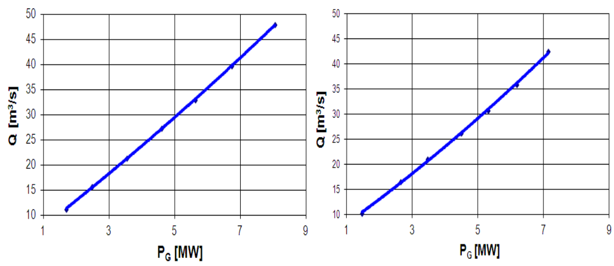

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Fig. 6. Characteristics of consumption for HPP Toteşti II HA1 (a) and HA2 (b)

After performing the calculations, efficiency turbine performance characteristics were drawn, for these three hydropower plants. These efficiency characteristics are shown in Fig. 7 - 9.

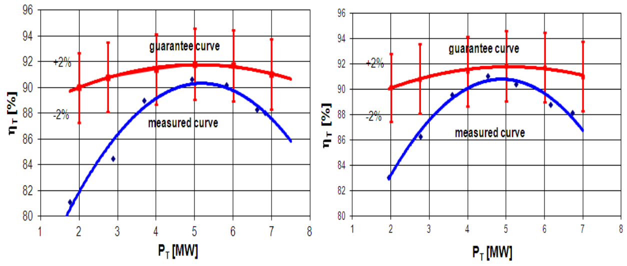

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Fig. 7. Measured and guaranteed efficiency characteristics for HPP Păclişa HA1 (a) and HA2 (b)

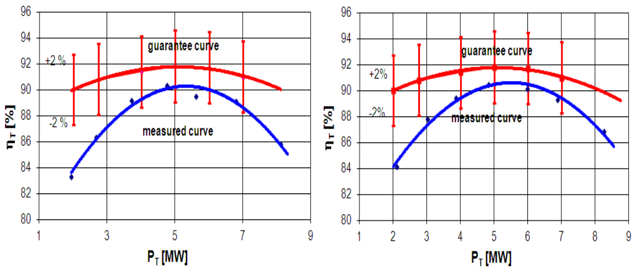

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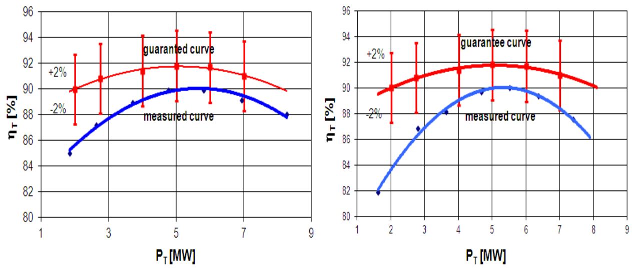
Fig. 8. Measured and guaranteed efficiency characteristics for HHP Toteşti I HA1(a) and HA2(b)



a) b)

Fig. 9. Measured and guaranteed efficiency characteristics for HHP Toteşti II HA1(a) and HA2(b)

As it can be seen in Fig. 7 - 9 most of the operating range of the efficiency characteristics of the turbines from the three hydopower plants determined by *in situ* measurements generally falls within the uncertainty band of 2% compared to the guaranteed performance characteristics. The *in situ* tests confirmed the achievement by the hydro-units from the three analyzed hydropower plants of the efficiency guarantees.

Based on the efficiency characteristics drawn following the efficiency tests performed *in situ* (Fig. 7, 8 and 9), the optimal areas of operation of the hydro units in the three hydraulic power plants were determined. Optimal areas are those areas where the turbine efficiencies have maximum values, over 88% and operation is safe without the occurrence of the cavitation phenomenon.

According to Fig. 7 the optimal operating areas of hydro-units in HPP Păclişa are between 3.5 [MW] ÷ 6.6

[MW] for HA1, respectively, between 3.1 [MW] ÷ 6.7 [MW] for HA2.

The maximum efficiency at CHE Toteşti I is 90.63 [%] for HA 1 and 91.04 [%] for HA 2.

According to Fig. 8, the optimal operating areas of the hydro-units in HPP Toteşti I are between 3.3 [MW] – 7.7 [MW] for HA1, respectively, between 3.2 [MW] – 7.2 [MW] for HA2.

The maximum efficiency at CHE Toteşti I is 90.32 [%] for HA 1 and 90.38 [%] for HA 2.

According to Fig. 9 the optimal operating areas of the hydro-units in HPP Toteşti II are between 3.1 [MW] – 7.8 [MW] for HA1, respectively, between 3.4 [MW] – 7.2 [MW] for HA2.

The maximum efficiency at CHE Toteşti I is 89.94 [%] for HA 1 and 90.19 [%] for HA 2.

By operating the hydro-units from the three hydropower plants within the aforementioned optimal areas, an energy gain of at least 2 [%] can be obtained.

At an average net head of 17.9 [m], if HPP Păclişa operates with both groups at maximum power 12.2 [MW] the maximum efficiency will not be obtained. The optimal operating range according to fig. 10 is between 5 ÷ 9 [MW].

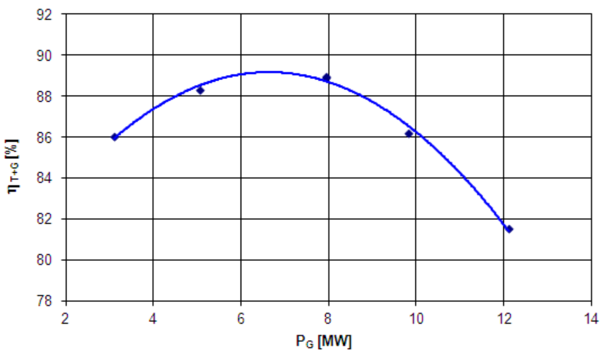


Fig. 10. Hydro unit efficiency - power characteristic for HPP Paclişa

At an average net head of 17.9 [m] if HPP Toteşti I operates with both groups at maximum power 13.8 [MW], the maximum efficiency will not be obtained. The optimal operating range according to fig. 11 is between 6.8 ÷ 11.5 [MW].

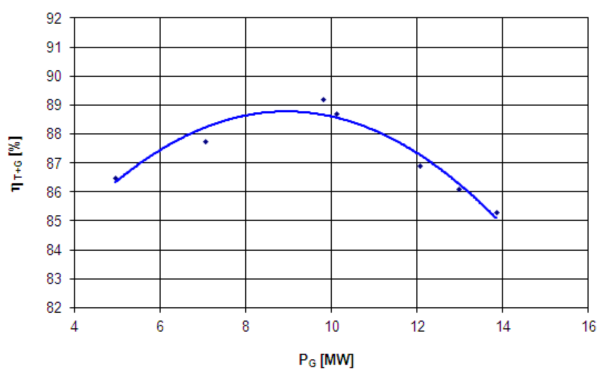


Fig. 11. Hydro unit efficiency - power characteristic for HPP Totesti I

From figures 10 and 11 it can be seen that if Păclişa HPP works with both hydro units, the maximum efficiency is 88.87 [%] and it corresponds to a power of 7.95 [MW]. If Toteşti I HPP works with both hydro units the maximum efficiency is 88,68 [%] and it corresponds to a power of 10.10 [MW].

Analyzing the results obtained from the efficiency tests performed *in situ* at the hydro units in the three hydropower plants, it can be observed that an operation of the hydro units at a lower power than the maximum power but at a maximum efficiency will minimize the turbine flow and lead to an economic operation. It would also increase the electricity production that can be obtained by the superior capitalization of the same annual water stock.

It was also observed that only using a single hydro unit versus two, in optimal discharge conditions, the daily energy production can be increased by over 1 [%].

4. GOALS OF THE HYDRAULIC TURBINE EFFICIENCY TESTS AND APPLICATION OF THE EFFICIENCY TESTS RESULT

The main goals of hydraulic turbine efficiency tests are shown as following:

- Searching for the high efficiency conditions in the operating area by absolute or relative efficiencies to instruct the hydro-unit operation and increase the water power utilization rate, so as to maximize the output of a single hydro-generator unit;

- Comparing the absolute efficiency of different hydro-generator units under same operating conditions by absolute efficiency to support scientific dispatch and economic operation in hydropower plants, in order to maximize the output of the station;

- Verifying the efficiency parameter meets the command in contract or not, by comparing the measured value with the contract one;

- Calibrating the spiral case differential pressure coefficient of same type turbines by absolute discharge and spiral case differential pressure measurement;

- Searching for Kaplan unit on-cam relation by absolute or relative efficiency measurement to assure the stable and high efficiency operation of the hydro-unit.

Application of the efficiency test results is shown as following:

- Economic operation for hydropower plants. Scientists and engineers have done many works about hydropower plant economic operation combining the unit efficiency and stable operating conditions, and the research results have been applied in practice. As for a single unit, it should be operated under the high efficiency operating conditions. As for a plant, the overall efficiency should be maximized to use the water resource sufficiently [13]. Based on the result of references [14], 1 [%] up to 2 [%] of total annual power generating capacity could grow if an optimized operating strategy was performed according to the actual river discharge.

- On-cam relationship confirmation for Kaplan turbines. It is dangerous for Kaplan turbine operated under off cam conditions because efficiency is low and the stability is poor. The on-cam curve can be gotten by the relative efficiency test so as to guarantee the high efficiency and stable operating for Kaplan turbine.

- Determination of optimal operating areas of hydraulic turbines. Turbine operation within optimal operating areas will both increase the amount of energy supplied as well as an increase in operational safety by avoiding areas with an increased cavitation potential.

5. CONCLUSION

The authors' contribution consisted of a brief presentation of the purpose, the measurement method used to determine the absolute discharge and the calculation of hydraulic turbine efficiency. Authors present the results obtained and the application of efficiency test results to Kaplan type hydraulic turbines that equip three low head cascade hydropower plants located in the arrangement of Râul Mare downstream.

Also in the paper were reviewed the main direct and indirect methods that are used to determine the absolute efficiency of a hydraulic turbine that equips a hydroelectric power plant.

Although in the last period huge progress has been made in the case of the flow measurement, *in situ* determination of this essential parameter in hydraulic turbine performance tests is often a major challenge even for experienced test teams.

This is true especially for hydraulic turbines that equip low head hydropower plants, where discharge determination is often the only option. Use of the current-meter method is still the most reliable approach in such a case, even if further progress of the scintillation techniques of the velocity field may change this situation in the future.

Index or simplified methods, based on determining the wicket gate opening relationship - the power at the generator terminals tests are sometimes used to establish the optimum on-cam in the case of turbines with double adjustment, without having to determine the turbine discharge.

These index methods due to their limited accuracy can only be recommended for determining the temporal states (preliminary) of the hydraulic turbines that equip the small hydropower plants (SHPP).

Although numerous absolute efficiency tests/relative efficiency tests have been performed as well as numerous researches for implementation of the results of these efficiency tests, some scientific research being applied in practice, there are still some related points especially for efficiency tests at high hydropower plants, which have not been fully resolved and still require increased attention.

Selection of the method for determining the efficiency of a hydraulic turbine. The thermodynamic method is recommended to determine directly the absolute efficiency. Other methods such as the current-meter method, dilution method, Gibson method are recommended to determine indirectly the efficiency of a hydraulic turbine.

According to the specialized literature, regarding high power and high head hydropower plants, it is more viable to determine absolute efficiency online, using a flow meter with ultrasounds. If the test is performed only once and it is not in real time, it may be used a thermodynamic method.

Existing problems in differential pressure measurement. The main problem in differential pressure measurement is blocking the pressure valves because many hydropower plants have more than 35 years of operation. The problem of blocking the pressure valves from the spiral chamber of the turbine may appear even after a short time of operation. It is recommended to clean and clear the pressure taps during the periodic inspections if is necessary, so it can be guaranteed a good state of pressure taps.

NOMENCLATURE

Q [m^3/s] - discharge
Δh [m] - pressure difference on taps of spiral case
k [m^{2,5}/s] - discharge coefficient constant
ρ [kg/m^3] - water density
H [m] - head
g [m/s^2] - gravity
A [m^2] - area of the measurement section
P_H [kW] - hydraulic power
P_G [kW] - active generator power
P_T [kW] - is turbine power
η_{T+G} [-] - hydro unit efficiency
η_T [-] - turbine efficiency
η_G [-] - turbine efficiency

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REFERENCES

[1] Adamkowski, A. - Essential methods of SHP efficiency testing. Testing hydraulic performance of water turbines, Institute of Fluid Flow-Machinery, Gdansk, POLAND September 10-11th, 2009
[2] *** IEC 41 1991-11 - Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pumps-turbines, Geneva, Switzerland, 3th. edition 1991
[3] *** SR EN 60041 - Încercări de recepţie efectuate pe maşina reală, pentru determinarea performanţelor hidraulice ale turbinelor, pompelor de acumulare şi turbinelor – pompe, 1st. edition 2003.
[4] *** ISO 3354 - Measurements of clean water in closed conduits. Velocity-area method using current-meters in full conduits and under regular flow conditions, International Organization for Standardization, 2008
[5] *** IEC 62006 - Hydraulic machines. Acceptance tests of small hydroelectric installations, 1st. edition 2010.
[6] *** ASME PTC 18 American National Standard, - Hydraulic turbines and pump - turbine performance test codes, 3th. Edition NY-USA, 2002 (consolidation of ASME 18-1992 and ASME 18.1-1978)

[7] Adamkowski A., Janicki W., Lewandowski M. - Measurements of Discharge through a Pump-Turbine in Both Flow Directions Using Volumetric Gauging and Pressure-Time Methods, Published in Energies 2020, 13(18), 4706; *https://doi.org/10.3390/en13184706*

[8] Zhou X., Fulin C., Youping L. - Ultrasonic FlowMeasurement Accuracy Analysis Based on CFD Technology, Hydraulic Power Automation and DamMonitoring.2010,34(3):32-34

[9] Chen Q, Wu J. - Research on the inherent error of ultrasonic flowmeter in non-ideal hydrogen flowfields, International journal of hydrogen energy, 2014 - Elsevier

[10] Baidar B., Nicolle J., Trivedi C., Cervantes M. J.- Winter-Kennedy Method in Hydraulic Discharge Measurement: Problems and Challenges, International Group for Hydraulic Efficiency Measurement, Linz, Austria 2016, pp. 1– 12.

[11] Baidar B. – A Sensitivity Analysis of the Winter-Kennedy Method, Licentiate Thesis, ISSN 1402-1757, Printed by Luleå University of Technology, Graphic Production 2018

[12] *** ICEMENERG - Determining the technical powers and performances of the 7.95 MW Kaplan hydro-units (HPP Păclişa, HPP Toteşti I, HPP Toteşti II), Contr. no. 130/2016

[13] Youping L., Yongzhen Y., Jian C. - Discussion on Start-up Strategies of hydraulic power units of Three Gorges Right Bank Plant, Yangtze River. 2016, 47(4):84-87

[14] Cavalier J. - Iso-Power cam curve testing for optimal blades/wicket gates law for Kaplan Turbines, IGHEM2020, Grenoble, France, August 24-25, 2020