TURBINE EFFICIENCY DETERMINATION IN HYDROPOWER PLANTS - PRACTICAL APPLICATION FOR A CASCADE OF HYDROPOWER PLANTS

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Abstract

In this paper, the authors briefly present the methods for determining in situ the efficiency / performance of a hydraulic turbine as well as the purpose, the necessity of applying the methods of in situ determination of the efficiency of the 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 the paper are presented the results of the efficiency tests carried out at a cascade of three hydropower plants, form Romania, from the arrangement of the Râul Mare downstream.

Keywords: hydropower plants, discharge determination, turbine efficiency, in situ tests, hydro-unit.

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 plants and of multiple plants that operate in a coordinated manner. Optimization has been an important focus in recent 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 is used such as: IEC 41 [2] respectively SR EN 60041[3], in compliance with conditions for achieving measurements provided for 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]. Because 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.

Methods for determining the efficiency of hydraulic turbines

Hydraulic turbine efficiency determining includes absolute efficiency methods and relative efficiency methods.

Direct method of determining absolute efficiency

A representative absolute efficiency method is the thermodynamic method. The method 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 outlet of the 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.

Indirect method of determining absolute efficiency

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 are so large and the water head are very high.

As for current-meter method, because of the influence of the mounting bracket and the current meters on the flow regime, the measurement precision will decreases absolutely. Further more, it is difficult to install the mounting bracket before the runner of large diameter, high water head hydraulic turbines, and the installation of the bracket 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 hydro-generators, the discharge maybe reach 350 m^3/s, tracer methods is also not available in engineering application.

From the view of present technology and engineering application, it is viable and using 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 parameter, integration method on the accuracy of the ultrasonic flow meter [8], so that we can increase the accuracy of the ultrasonic flow meter and its accuracy can meet the command of the turbine absolute efficiency test.

Relative efficiency measurement method

Turbine relative efficiency is measured by differential pressure devices [9]. The principle of differential pressure methods is as following. When water with a certain velocity passes 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 the Bernoulli equation, the discharge Q is determined according to IEC41. This method is called the Winter-Kennedy method.

The Winter-Kennedy method was initially described by Winter I. A. and Kennedy A. M. in their paper [10]. IEC 41 considers this as a relativ method and can only be used as a part of field acceptance test if the method is calibrated by absolute method considered in the standard. The standard also suggested that the Winter-Kennedy method cannot be used to check the power guarantee 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 flow is dependent on the measured pressure difference between two corresponding points located in flow system according to the formula:

$$Q = k(\Delta h)^n \quad (1)$$

where, Q is dischaege, 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 and inner side of the turbine spiral case due to the centrifugal force acting on the curved streams of liquid in the spiral case. The possible location of the pressure taps is presented on Figure 1a according to IEC 41 Standard for a concrete half-spiral chamber of the 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 Figure 1b, and with a bulb turbines (without a spiral) is shown in Fig. 1c.

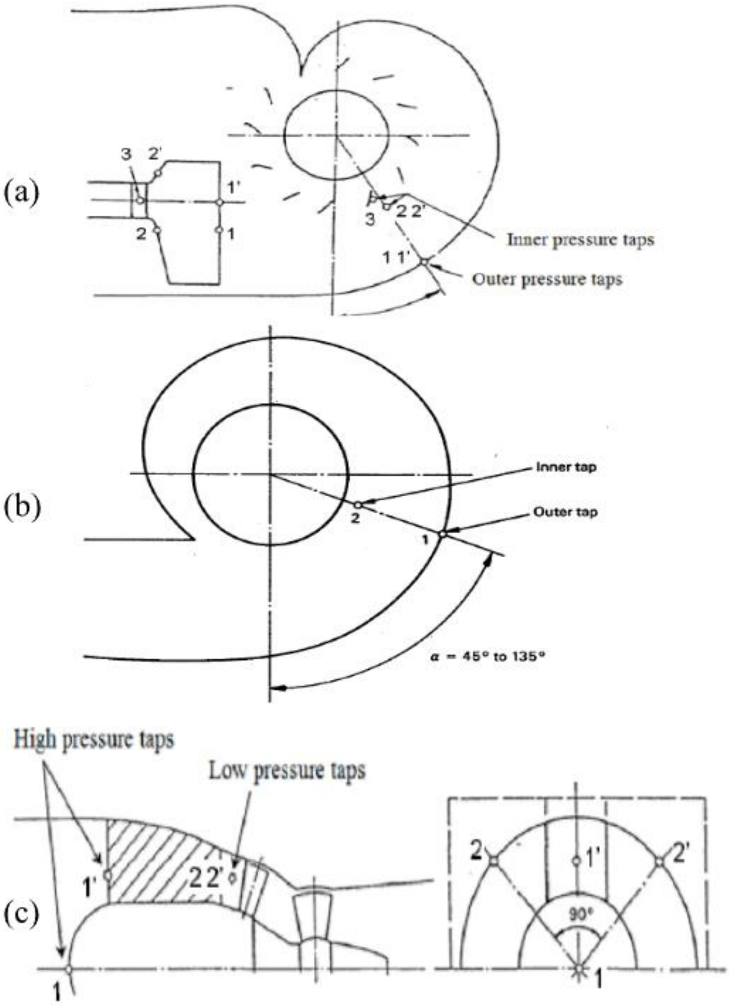


Figure 1. Location of differential pressure taps in:
(a) Kaplan turbine equipped with a concrete half-spiral chamber;
(b) Francis turbine; and (c) bulb turbine [1]

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, the tightness of the measuring system, and easy access to the equipment) and to use suitable measuring equipment (differential pressure transducer of high class).

Determining the efficiency of hydraulic turbines for hydropower plants in cascade.

In order to exemplify the efficiency tests at the hydroelectric power stations, it was chosen a cascade of three hydroelectric power stations from the Păclişa lake sector - the escape channel HPP Totesti II from the arrangement of the Râul Mare downstream [11].

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 dam central and the two downstream power stations, Toteşti I and Toteşti II, which are placed on derivation channels have the design characteristics (installed power, installed flow, gross head, net head) and two Kaplan type KVB 8.4-21 turbines each.

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

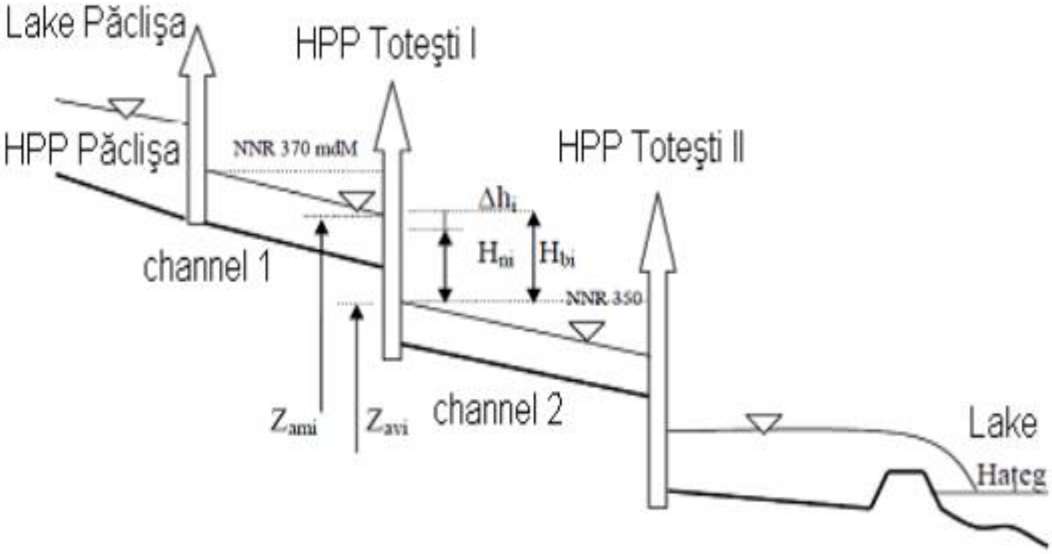


Figure 2. Scheme of the Păclişa lake sector - HPP Toteşti II escape channel

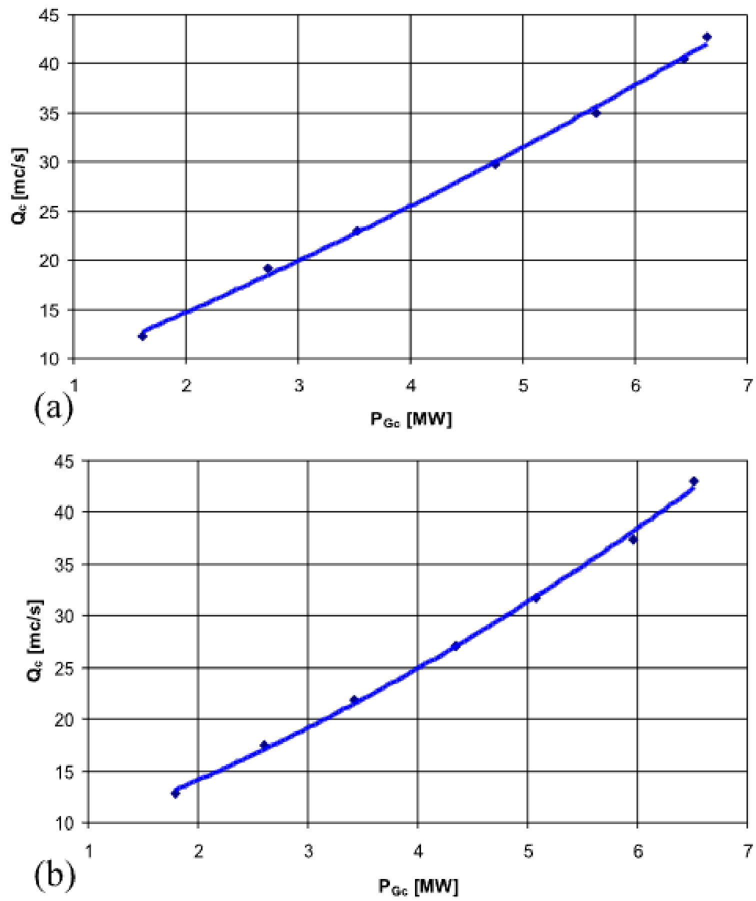


Figure 3. Characteristics of consumption for HHP Păclişa HA1 (a) and HA2 (b)

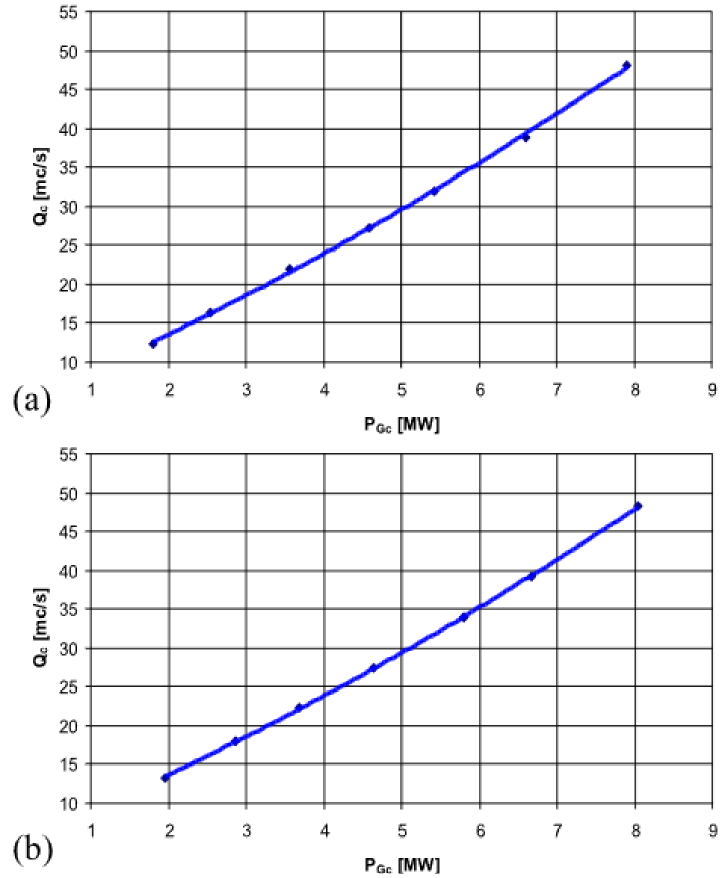


Figure 4. Characteristics of consumption for HHP Toteşti I HA1 (a) and HA2 (b)

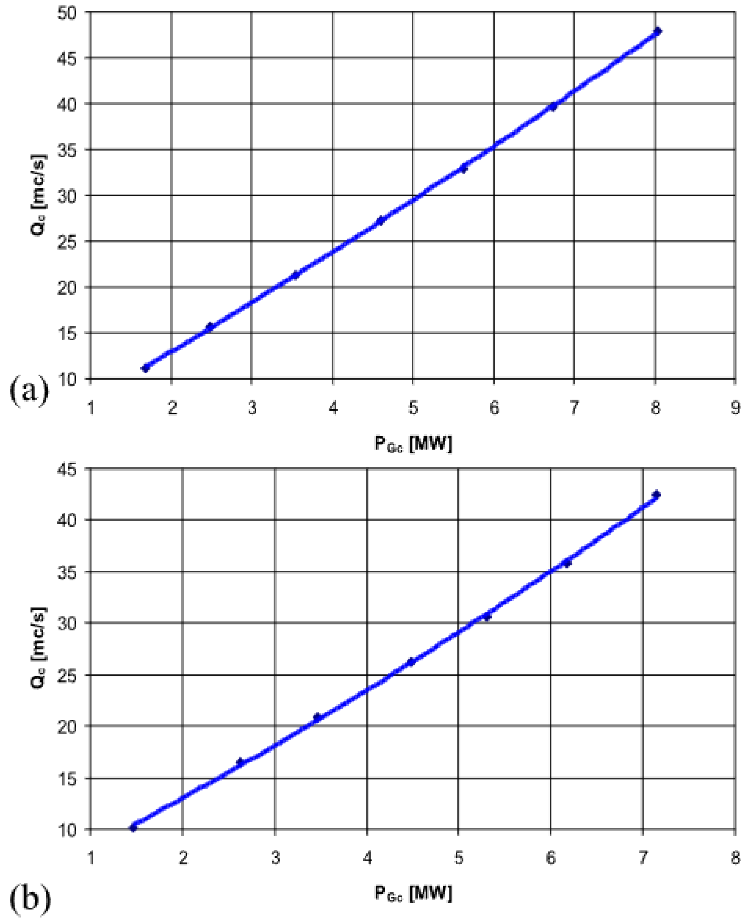
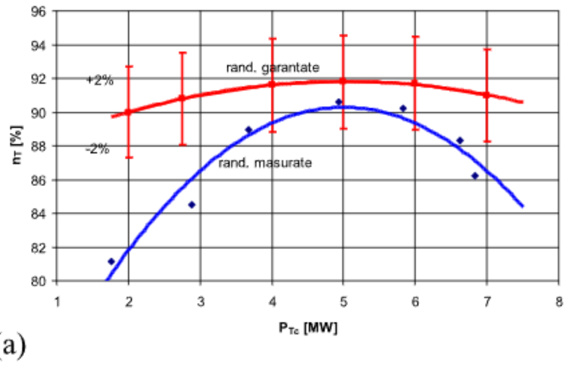
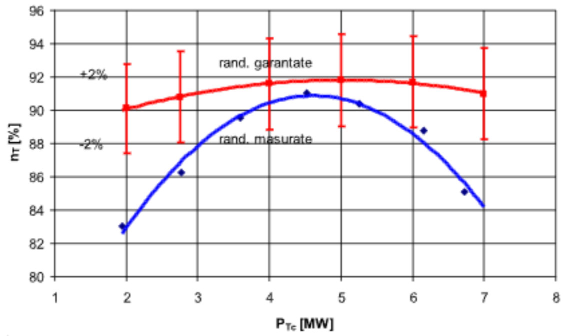


Figure 5. Characteristics of consumption for HPP Toteşti II HA1 (a) and HA2 (b)

After performing the calculations, efficiency turbine performance characteristics were drawn, for the three hydropower plants. These efficiency characteristics are reproduced in Figure 6-8.

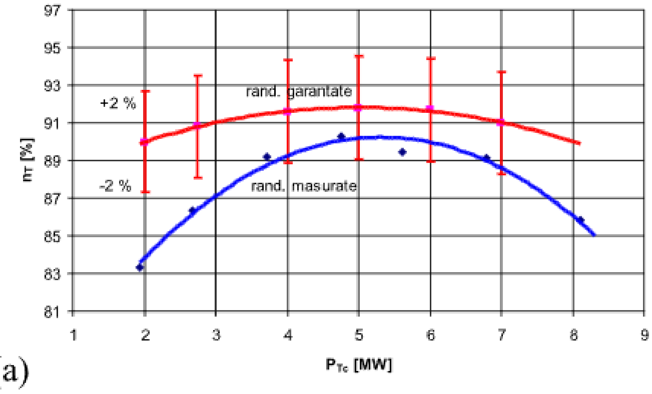


(a)

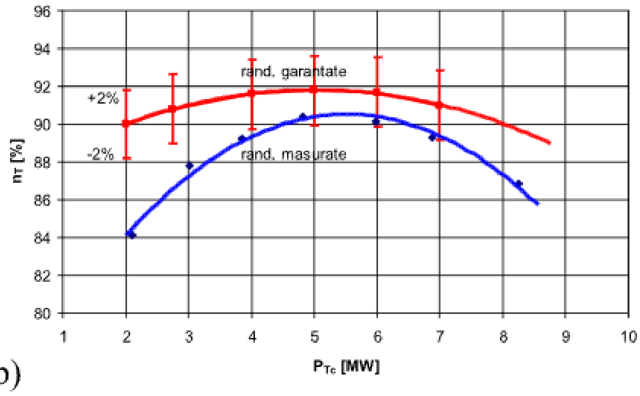


(b)

Figure 6. Measured and guaranteed efficiency characteristic for HPP Păclişa HA1 (a) and HA2 (b)

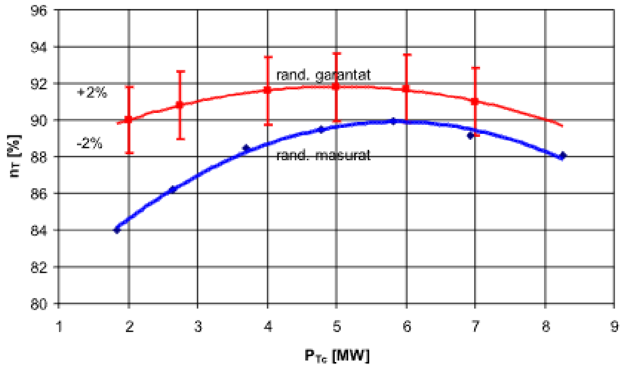


(a)

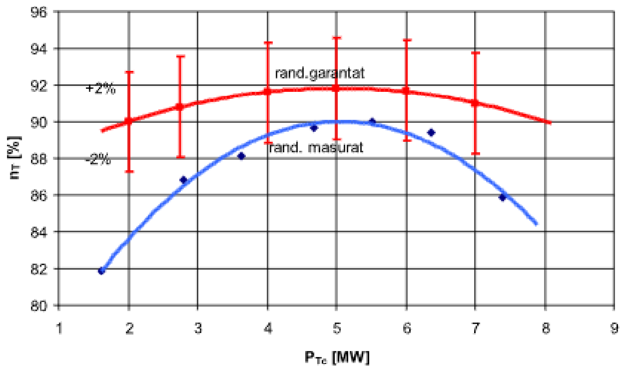


(b)

Figure 7. Measured and guaranteed efficiency characteristic for HHP Toteşti I HA1 (a) and HA2 (b)



(a)



(b)

Figure 8. Measured and guaranteed efficiency characteristic for HHP Toteşti I HAII (a) and HA2

As can be seen in Figure 6-8 most of the operating range of the efficiency characteristics of the turbines from the three plants determined by *in situ* measurements generally fall 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.

According to Figure 6 the optimal operating areas of the 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.

According to Figure 7 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.

According to Figure 8 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.

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

Goals of the hydraulic turbine efficiency tests and application of the efficiency tests results

The goals main of hydraulic turbine efficiency tests is 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 hydopower plants, so as 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;

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

- Searching for the 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 it 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. Based on the result of references [12], 1% to 2% of total annual power generating capacity it 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, its 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 the 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.

Conclusions

Although in the last period huge progress has been made in the case of the discharge 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 the determination of the relation of the opening of the wicket gate - the power at the generator terminals and vibration tests are sometimes used to establish the optimum on-cam in the case of turbines with double adjustment, without having to determine the turbine flow rate.

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 the 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 power hydroelectric plants, which have not been fully resolved and still require increased attention.

Selection of the method for determining the efficiency of the 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 hydraulic 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 the is blocking the pressure taps, many hydropower plants have more than 35 years of operation. The problem of blocking the pressure taps 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 reviews if is necessary, so it can be guaranteed a good state of pressure taps.

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References:

1. Prodanovic D., Ivetic D., Milivojevic N., Vojt P. Flow measurement methodology for low head and short intake bulb turbines - Iron Gate 2 case. In IGHEM 2022 proceedings, Grenoble, France, 2022.
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. Bucureşti, România, 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. Geneva, Switzerland, 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. Neyestanaki M. K., Dunca G., Jonsson P., Cervantes M. J. Experimental Study of the Pressure-Time method with potential application for low-head hydropower. Journal of Fluids Engineering, July 2023, Vol. 145 / 071205-1.
8. Ivan M., Lionel M., Cornel I., Leo B., François A., Henda D. Ultrasonic flow measurement under dynamic conditions and geometrically unsteady conditions. In IGHEM 2022 proceedings, Grenoble, France, 2022.
9. Zhou X. Z., Wang Z. W., Ahn S. H., Xia M., Yi Z. C. Experience Measurement of Winter-Kennedy method on low head tubular turbine units. IOP Conference Series: Earth and Environmental Science. Vol. 627. No. 1. IOP Publishing, 2021.
10. Winter I. A. , Kennedy A. M. Improved type of flow meter for hydraulic turbines. American Society of Civil Engineers, Proceedings, vol. 59, no. 4, April 1933.
11. 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.
12. 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.