



# Research Progress of Field Efficiency Testing Methods for Prototype Hydraulic Turbines

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**Abstract.** The turbine efficiency is an important factor for reflecting the turbine's hydraulic performance, which plays an important role in guiding the design, manufacture and economic operation of turbine. In recent years, with the continuous improvement and innovation of sensing technology and modern electronic technology, some measurement methods have also been continuously developed. The recent research progress from the research on the field efficiency testing methods of turbines is reviewed herein from four commonly used testing methods of field efficiency of prototype hydraulic turbine, namely, flow-meter method, ultrasonic wave method, pressure-time method and thermodynamic method. The characteristics, existing problems and improved methods of different testing methods are discussed and analyzed, and the development trend of field efficiency testing methods of prototype hydraulic turbine is also pointed out.

**Keywords:** turbine efficiency; measurement methods; efficiency testing system; research progress

## 1 Introduction

As an important equipment for energy conversion of hydropower station, the conversion efficiency of turbine is an important index to reflect the hydraulic performance of turbine, and also one of the important bases to evaluate the economic operation of hydropower station. The efficiency characteristic curve of the turbine is usually obtained by the conversion of the runner model test, but there is often a certain difference from the actual efficiency of the turbine after the unit is run<sup>[1-2]</sup>, so it is particularly necessary to test the efficiency of the prototype turbine. There are many test methods for prototype turbine efficiency test. According to the different measurement methods, the main ones are pressure-time method, current meter method, ultrasonic method, thermodynamics and so on<sup>[3]</sup>. Among them, the pressure time method deduces the flow conversion efficiency according to the unstable pressure change in the water pipeline<sup>[4]</sup>, but it has strict requirements on the length of the pressure steel pipe, and has certain destructive effects on the unit's operating performance<sup>[5]</sup>, so it is not widely used; Flow meter method through the measurement section flow rate distribution of

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mathematical calculation, and then obtain the turbine flow and efficiency, but the site installation is cumbersome, the calculation method is more complex<sup>[6]</sup>; Ultrasonic method to ultrasonic as a medium to obtain the flow rate, and then obtain the turbine flow and efficiency, although the site installation is simple, but the measurement accuracy is not high<sup>[7]</sup>; The thermodynamic method based on the first law of thermodynamics by measuring the turbine inlet and outlet section temperature difference to achieve turbine efficiency measurement<sup>[8]</sup>, no need to measure the turbine flow, but the accuracy of the temperature measurement instrument is higher.

This paper first briefly introduces the principle and characteristics of the above turbine field efficiency test methods, and then reviews the research and application progress of each turbine field efficiency test technology at home and abroad in recent years, and comments the application range and advantages and disadvantages of different test technologies, and puts forward the best test method for different head and different flow turbine field, and looks forward to the future development direction.

## **2 Research Progress and Trend of Turbine Efficiency Measurement Methods**

### **2.1 Research Progress and Trend of Thermodynamic Measurement of Turbine Efficiency**

The thermodynamic method is a method to calculate the energy conversion between the runner and the water flowing through the runner according to the law of conservation of energy (the first law of thermodynamics). Water flowing through the runner in addition to obtain useful power to make the runner rotate, but also because of friction, vortex deflow and a series of hydraulic losses into heat energy, and then make the water temperature rise, so that the water flow into the turbine inlet and outlet section produce a certain temperature difference<sup>[9]</sup>. Therefore, the thermodynamic method is to measure the turbine efficiency by measuring the temperature difference between the inlet and outlet of the turbine.

The study of thermodynamic method in the measurement of hydraulic machinery efficiency was first put into practice by Barbillon and Poisson with mercury thermometer on hydraulic turbine<sup>[10]</sup>. Later, Willm and Campmas<sup>[11]</sup> improved the test method on this basis and put it into practice on reversible hydraulic turbine. In order to compare the advantages of thermodynamic method for measuring turbine efficiency, Muciaccia<sup>[12]</sup> and Dahihaug et al<sup>[13]</sup> designed turbine efficiency test experiments, compared thermodynamic method with other test methods, and found that the uncertainty of thermodynamic method for measuring turbine efficiency could be lower. Liu Xin et al<sup>[17]</sup> tested the performance of 58 pumps by thermodynamic method and traditional test methods such as electromagnetic flow meter and ultrasonic flow meter, obtained some basic application principles of thermodynamic method, and found that thermodynamic method significantly depends on the sensitivity and stability of temperature probe, and in complex flow conditions, the measurement accuracy of thermodynamic method is significantly higher than that of traditional test method. The accu-

racy of the general thermodynamic method to determine the turbine efficiency is closely related to the selection of measuring section, water head control and equipment installation<sup>[14-17]</sup>. IEC technical standards point out that the thermodynamic method can obtain better measurement accuracy under the condition of hydraulic specific energy exceeding  $1000 \text{ Jkg}^{-1}$  (water head  $> 100\text{m}$ )<sup>[18]</sup>. With the development of high precision temperature measurement technology and computer technology, Hulaas et al<sup>[19]</sup>, successfully applied the thermodynamic method in the efficiency of 50m low head turbine, and pointed out that if the test equipment can meet the requirements of measurement accuracy, the applied head is no longer a factor restricting the application of thermodynamic method. In addition, Grego<sup>[20]</sup> and Staubli et al<sup>[21]</sup>, through a large number of field practices, found that the energy distribution of the low pressure side section of the turbine is an important factor affecting the measurement efficiency of the thermodynamic method. Zhang Kui and Zhou Ye<sup>[17]</sup>, aiming at 3A hydropower station in Shang cui Shu li, Nepal, carried out a case study of turbine efficiency test using thermodynamic method, and obtained the relationship between the improved equipment layout scheme and the measurement accuracy of turbine efficiency. Dong Hongkui et al<sup>[22]</sup>, studied the unit efficiency of Lihe River Hydropower Station in Yunnan by thermodynamic method, and pointed out that the stability of the inlet water temperature of the turbine has a crucial influence on the measurement of efficiency.

In order to make up for the deficiencies of thermodynamic method in the actual measurement of turbine efficiency, some scholars studied and improved the testing and calculation methods of thermodynamic method for measuring efficiency. Among them, Cao Dengfeng et al<sup>[23]</sup>, proposed an improved method by iterative calculation of low-pressure side velocity, turbine flow and efficiency, aiming at the problem that the uneven distribution of flow velocity on the low pressure side affects the accuracy of test results. And the application practice was carried out in a certain impact hydropower station with a rated head of 650m, and it was found that the turbine efficiency curve measured based on the improved method was basically consistent with the efficiency curve converted from the model test. Li Jinwei et al<sup>[24]</sup>, improved the arrangement of measuring instruments at the measurement section of the low-pressure side of the draft pipe, and selected 12 load conditions near the guaranteed value of the purified water head of 325m for testing and verification. The test results show that the improved thermodynamic test method is feasible. Wang Juan and Li Chunxi, in order to solve the problem that the temperature difference of the exit section affects the accuracy of the test efficiency of the thermodynamic method, put forward a new mathematical model based on the thermodynamic method to accurately measure the efficiency, and carried out a successful practical application in a unit.

## **2.2 Research Progress and Trend of Measuring Turbine Efficiency by Current Meter Method**

In the field efficiency test of turbine, the efficiency can be directly measured by thermodynamic method, and the flow rate needs to be measured by other test methods in order to measure the efficiency characteristics of turbine. Current meter flow meas-

urement technology is a relatively old method compared with other test methods, practical application experience is mature, rarely by electromagnetic, temperature, human and other factors interference, is also one of the basic methods of measuring turbine flow recommended by IEC<sup>[25]</sup>. Using the current meter method to measure the flow of the turbine, it is necessary to arrange multiple current meters on the flow measurement section, by measuring the flow rate of each measuring point of the cross section, and then the flow rate of the cross section by numerical integration, to obtain the flow rate of the turbine<sup>[26]</sup>. Therefore, it can be seen that the most important instrument in the process of measuring the flow rate of the turbine by the current meter method is the current meter, which directly affects the accuracy of the measurement results. A long time ago, the function of the current meter developed is relatively simple, and the use is complicated and cumbersome, especially the traditional rotor current meter is not only large, bulky, inconvenient to carry, but also does not consider the impact of turbulence on the measurement accuracy. With the development of sensing technology and electronic information technology, scholars have carried out more in-depth research on the new type of current meter. Wang Peiyun's team<sup>[27]</sup> independently developed and designed the BH-1 portable rotor current meter to make up for the shortcomings of the traditional rotor current meter, improve the anti-interference ability and measurement accuracy of the system, and have no special requirements for the measured flow. Amy and Roger<sup>[28-29]</sup> used digital dual-frequency Doppler technology to develop a portable Doppler flow meter, which not only has complete measuring functions, but also is easy to implement in the field, and can effectively measure the fluid flow containing solids or gases. Based on the test principle of current meter method and LabWindows CVI platform, Xiao Zhihui team<sup>[30]</sup> of Wuhan University researched and designed a set of hydraulic turbine flow efficiency test system suitable for multi-working conditions. The system has good measurement accuracy, strong expansibility and high human-machine interaction, and has been verified in practice in actual hydropower station, and achieved good test results. Tong Gang and Cao Shuchao<sup>[31]</sup> based on many years of field test experience, research and design a portable intelligent flow velocimeter that can simultaneously measure the flow rate and flow rate of multiple flow channels, and in the field test, the practice verification has been carried out and obtained good results.

With the continuous development of current meter, scholars have carried out in-depth research and practical application on the on-site efficiency of hydropower units by using current meter method, in order to provide reference for similar field tests through the completed practical test cases. Wang Bangxu et al<sup>[26]</sup>, used the current meter method to study the efficiency characteristics of the A1 mixed-flow unit after the transformation of Zhelin Hydropower Station, and obtained the performance curve to guide the operation of the unit, and further verified the rationality and accuracy of the method of measuring the turbine efficiency based on the current meter method. Zhang Wei and Wang Lin<sup>[32]</sup> studied the efficiency characteristics of the unit of Xinfengjiang Hydropower Station through the current meter test method, which solved the flow test problem of large hydropower station well and also provided a useful reference case for the field efficiency test of similar large hydropower station. Li Fulan<sup>[33]</sup> used the im-

proved current meter test system to test the field efficiency of a mixed-flow unit, and obtained the results consistent with the original test value. In addition, Sun Yibao<sup>[34]</sup> used the current meter method to systematically study the field efficiency of large axial flow pump. These search results show that the current meter method can be applied regardless of the size of the pump head and flow.

In addition, the flow calculation analysis method based on the current meter method has also been paid attention to. Carter and Anderson<sup>[35]</sup> used the area integral method to calculate and analyze the cross section flow rate, and analyzed the main sources of error, and pointed out that the uncertainty of the calculation efficiency of the area integral method was about 2%. Guo Maoxiong and Wu Changsheng<sup>[36]</sup> studied the approximate calculation method of flow measurement by the current meter method of circular cross section, and verified by comparing different integral methods, obtained the approximate mathematical model for calculating the flow of circular section. Kong Qinghuai et al<sup>[37]</sup>, deeply studied the calculation principle of calculating the flow of pipeline section according to the space column, and based on this, proposed to use the velocity area method of the current meter to measure and calculate the flow of the turbine. Zhou Ye et al<sup>[38]</sup>, studied the flow analysis method of calculating the measured section through each measuring point, and innovatively proposed the flow calculation method using the flow integration method. The field practice results show that the flow results obtained by this method are higher than the requirements of conventional measurement accuracy.

### **2.3 Research Progress and Trend of Ultrasonic Measurement of Turbine Efficiency**

Ultrasonic method is based on the propagation speed of ultrasonic wave in the fluid to obtain the flow rate, and then get the flow rate. combined with the measured power, water and other characteristics of the turbine efficiency test, get the efficiency of the turbine<sup>[23][39]</sup>. Because the ultrasonic method has the advantages of simple installation, strong applicability and high degree of automation after processing, it has been widely used in the field efficiency test practice of large and medium-sized and low head hydropower station units at home and abroad<sup>[40]</sup>. Shao Guohui et al<sup>[41]</sup> carried out in-site ultrasonic efficiency test based on No 2 unit of Kalen Hydropower III Station. The results have shown that the measured efficiency curve can well reflect the actual energy characteristics of the unit. Based on the efficiency test results, the experiential practice of using the ultrasonic method in in-situ efficiency testing of hydraulic turbines has been summarized. Shi Guihe<sup>[42]</sup> has studied the efficiency of No. 3 hydro-generator in Hanhua Hydropower Station in Pakistan using ultrasonic method, and compared it with the efficiency curve converted from model test. The results show that the experimental error of the efficiency measured by ultrasonic method is 1.94%, which meets the requirements of IEC specifications. Zhang Peng et al<sup>[43]</sup>, took the impact unit of Mayina hydropower station without thermodynamic method as the research object, and used ultrasonic method to measure the efficiency of the impact unit. The research results show that the ultrasonic method can realize the accurate measurement of the flow rate

of large pipe diameter and large wall thickness pipe. Feng Yanmin et al<sup>[44]</sup>. conducted a field test on the efficiency characteristics of a mixed-flow unit with ultrasonic flow measurement method, and analyzed the relationship between the head loss of diversion water and the square flow rate, and corrected the volute pressure differential flow coefficient according to the test results.

In addition, scholars also based on the ultrasonic test principle, the use of modern sensing technology to develop and design a variety of measuring systems. Chen Xupeng et al<sup>[45]</sup>. Integrated new ultrasonic current measuring equipment, efficiency testing system and acquired software processing system, researched and designed a test system for measuring turbine efficiency based on ultrasonic method, and carried out practical verification in Xiluodu Hydropower Station. The results show that the system has good test accuracy and reliability. Zhou Erbao et al<sup>[46]</sup>. Adopted ultrasonic flow meter, combined with other data acquisition and analysis tools and introduced efficiency calculation and analysis algorithm to set up the unit efficiency online monitoring system, and realized the real-time performance monitoring and analysis of the unit. On the basis of obtaining the flow rate in the pipeline by using the advanced multi-channel ultrasonic measuring instrument, Tang Jiqun et al<sup>[48]</sup>. developed an online monitoring system for real-time collection and measurement of the efficiency curve of the turbine unit of a small hydropower station, and guided the acquisition of the optimal efficiency area of the unit, providing technical support for the economic operation of the unit of a small hydropower station.

## **2.4 Research Progress and Trend of Hydraulic Turbine Efficiency Measurement Based on Pressure-time Method**

Pressure-time method is one of the measurement methods commonly used to measure the flow rate of hydraulic turbines mentioned in the national standard GB/T20043<sup>[49]</sup> and the International Electrotechnical Commission standard IEC60041<sup>[50]</sup>. Since 1923 Norman Rothwell Gibson first<sup>[51-52]</sup> proposed to measure the closed pressure pipeline flow measurement method - "Gibson method", also known as pressure-time method, the method has been developed for nearly a century. Its measuring principle is mainly through the pressure pipeline valve suddenly and quickly closed the water hammer phenomenon caused by the water pressure in the pressure pipeline changes, according to the change in the pressure pipeline water pressure value and process, calculate the turbine flow before the valve closed. Pressure-time method of measuring turbine flow is based on professional knowledge theory. In order to improve the accuracy and applicability of pressure Gibson method in the actual application process of hydropower station, scholars at home and abroad have studied the factors affecting Gibson method and the improvement method by theoretical and experimental analysis means. Based on model tests, M Suita et al<sup>[53]</sup>. carried out a study on the nature of error in the process of Gibson flow measurement, and found that guide vane closing time and pipeline friction coefficient are both factors that affect the flow measurement error. Adamkowski et al<sup>[54]</sup>. used pressure-time method to test and study the flow of hydropower station with curved diversion pipe, analyzed the influence of curved pipe on the accuracy of flow

measurement by pressure time method, and used Fluent fluid analysis software to conduct a comparative analysis. Jonsson et al<sup>[55]</sup>, proposed an improved unsteady Gibson method considering the addition of time acceleration in the process of flow calculation by Gibson method, and verified it through experiments and numerical simulation. The results show that the numerical error of flow obtained by the improved unsteady Gibson method is reduced by 0.4% compared with the classical Gibson method. Adamkowski and Waldemar Janicki<sup>[56]</sup> proposed a numerical analysis method for calculating unsteady fluid flow in pressure pipelines based on the elastic water hammer theory, which can effectively reduce the sensitivity of the upper integral limit. Domestic scholars Cheng Xinping and Wang Dingyi<sup>[57]</sup> studied the mathematical model of the pressure-time method for measuring the flow of hydraulic turbine, and proposed a mathematical model with elastic theory for error correction, and verified it by the field test of Danjiangkou Unit 1. The results show that high accuracy can be obtained when the elastic theory is used to calculate the flow.

In order to explore whether the pressure-time method can be applied to different working heads and different types of units when measuring the flow rate of turbines. Hulaa et al<sup>[58]</sup>. Used two test methods, pressure-time method and thermodynamic method, to conduct a comparative analysis and study on the flow rate and efficiency of a turbine in a hydropower station with a clean water head of 52m. The measurement results show that the relative error of efficiency obtained by using pressure-time method is between 0.5% and 1.15%. It also shows that the pressure-time method is suitable for the flow and efficiency measurement conditions of low head turbines. Kong Demin et al<sup>[59]</sup>. selected Xiaolangdi No. 1 large mixed-flow turbine unit under the condition of heavy sediment and used the pressure-time method to carry out the field efficiency test. The research results show that the efficiency curve obtained is in good agreement with the efficiency curve converted from the model. Based on the pressure-time method, Ou Xuexiu<sup>[60]</sup> tested the flow and efficiency of turbines with different working heads by using a test device developed for the head range of 14~760m. The results show that there are no discrete points in "T-test". Lin Taiju<sup>[61]</sup> used the pressure-time method to study the field efficiency characteristics of a mixed-flow unit with a working head of 30m at Huangtangkou Hydropower Station, and compared the test results with the volute differential pressure method and thermodynamic test methods.

### 3 Summary

Turbine efficiency is the key indicator of its hydraulic performance, which plays an important role in guiding the optimal economic operation of hydropower station. With the development of modern electronic technology and sensing technology, various kinds of testing techniques with different basic principles have been developed rapidly. In this paper, the main research results and development trends of hydraulic turbine field efficiency testing methods are summarized from four aspects: pressure-time method, current meter method, ultrasonic propagation time method and thermodynamic method. Although in recent years, the development of on-site efficiency and flow testing

technology of hydraulic turbines is becoming more and more mature and certain research result have been achieved, but with the development of hydropower equipment towards large-scale and high head, its structure is becoming more and more complex, which needs to be continuously studied and improved in the following aspects:

(1) At present, the research objects of turbine field efficiency testing are mainly concentrated in the aspects of mixed-flow units, reversible pump turbines and small impact turbines, etc. There is no discussion on the study of large-capacity high-head impact turbines, how to consider the unsteady characteristics of low-pressure side flow of large-capacity high-head impact turbines, design performance, operating condition range and structural installation mode, etc. Further research is needed to determine the applicable field efficiency test method and establish a reliable absolute efficiency evaluation mechanism for large capacity and high head impact turbines, so as to improve the field efficiency test system of prototype units.

(2) The test accuracy of the prototype turbine field efficiency is closely related to the working environment of the test instrument, the type of the unit, the mode of operation and other factors. By combining the field test and the numerical simulation calculation and analysis method, the main causes of the field test errors are compared and analyzed to provide a theoretical basis for improving the field efficiency test.

(3) Compared with other test methods in the efficiency measurement of prototype turbines, the current meter method has some shortcomings such as complex installation and calculation process, short detection period by flow channel water impact, etc. How to improve the measuring structure and calculation method of the current meter, so as to make the operation simple, low measurement cost, long service cycle, high measurement accuracy and wide popularization needs further research; At the same time, the turbine efficiency online monitoring system mainly focuses on the test method based on ultrasonic flow measurement and current meter flow measurement method indirect measurement efficiency, and can also consider the study of the integration of direct measurement of turbine efficiency thermodynamic method, so as to achieve the expansion of its system versatility.

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