An Improved Procedure in Efficiency Measurement on Pump-Turbine by Thermodynamic Method

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Abstract

Thermodynamic method is a practical solution to determine the turbine efficiency of heads in excess of 100m without need for discharge measurement directly. Efficiency measurement is performed on a vertical pump-turbine with 600m rated head by thermodynamic method in this paper. Measuring devices are designed to satisfy both the turbine and pump operating conditions. Determination of specific hydraulic energy, specific mechanical energy, discharge and efficiency of pump-turbine are discussed accordingly. To avoid the uncertain impact from unstable flow and velocity profile at low pressure section, an improved method to determine the turbine discharge is introduced, in which discharge may be worked out without need for flow velocity measurement at low-pressure section.

1. Introduction

As a key indicator of hydraulic performance, measured prototype efficiency is important to the acceptance of turbine. One of the difficulties in field test for turbine efficiency is discharge measurement, which is generally performed by current-meter method, pressure-time method, thermodynamic method, etc. Derived from the first law of thermodynamics, thermodynamic method is a practical solution to determine the turbine efficiency with no need for directly measuring the discharge. As a limitation, thermodynamic method is usually used for turbine with heads in excess of 100m to obtain evident temperature difference [1].

Thermodynamic method was firstly introduced by L. Barbillon and A. Poirso in 1920 [2]. G. Willm and P. Campmas improved this method in 1954 [3]. F. F. Muciaccia [4] and O. G. Dahlhaug [5] compared thermodynamics with other method and proved measuring uncertainty of thermodynamics lower than 1%. H. Hulaas [6] has performed thermodynamic test on a turbine with 50m head successfully. As temperature measurement techniques has improved a lot in these years, water head is not the dominant restriction to the application of thermodynamic method. During thermodynamic test, measuring accuracy of turbine discharge and efficiency is mainly affected by the various velocity distribution at low pressure section due to unstable flow and velocity profile [7] [8].

Efficiency measurement is performed on a vertical pump-turbine with 600m rated head by thermodynamic method. An improved procedure is introduced in this paper which shows that turbine discharge could be determined without need to measure flow velocity at low pressure section. Flow velocity determined by this procedure is the mean velocity at low pressure section which is more reliable than measurement directly. Corrective terms of specific mechanical energy and flow velocity at low-pressure section are iterated into the computation procedure, in which the final velocity is the mean velocity at low-pressure section and the final efficiency is more reliable rather than direct measurement. Determination of specific hydraulic energy, specific mechanical energy, discharge and efficiency of Pump-turbine are discussed accordingly.

2. Measuring method

When water passes through the turbine flow channel during operation, it will produce a series of losses caused by friction, vortex, flow separation, etc. All these losses shall convert to thermal energy and make the water temperature difference between high- and low-pressure section. Therefore, turbine output power, which presents as "specific mechanical energy", can be determined by measurement of the performance variables (pressure, temperature, velocity and altitude) and from the thermodynamic properties of water.

$$E_m = \bar{a}\left(p_{abs10} - p_{abs20}\right) + \overline{C_P}\left(\theta_{10} - \theta_{20}\right) + \frac{v_{10}^2 - v_{20}^2}{2} + g\left(z_{10} - z_{20}\right) + \delta E_m \qquad (1)$$

Where:

E_m, specific mechanical energy;

C_p, average water specific heat capacity;
a, average isothermal factor of water;
g, acceleration of gravity;
p_{abs10}, p_{abs20}, absolute pressure at high pressure section 10 and low-pressure section 20;
θ_{10}, θ_{20}, water temperature at high pressure section 10 and low-pressure section 20;
v_{10}, v_{20}, average flow velocity at high pressure section 10 and low-pressure section 20;
z_{10}, z_{20}, altitude of high-pressure section 10 and low-pressure section 20;
δE_m, the corrective energy term of specific mechanical energy.

Because it is difficult to directly measure in the flow passage, specific sampling vessels are usually used to determine specific mechanical energy. Therefore, the practical expression of specific mechanical energy is:

$$E_m = \bar{a}\left(p_{abs11} - p_{abs20}\right) + \overline{C_P}\left(\theta_{11} - \theta_{20}\right) + \frac{v_{11}^2 - v_{20}^2}{2} + g\left(z_{11} - z_{20}\right) + \delta E_m \tag{2}$$

Where:
Subscript 11 means high pressure measuring section 11 which locates at sampling vessel behind of main inlet valve of the unit.

The hydraulic energy before water goes into the runner, which presenting as “specific hydraulic energy”, can be determined by measurement of pressure, velocity and altitude at high pressure section 10 and low-pressure section 20:

$$E_h = \frac{p_{10} - p_{20}}{\rho} + \frac{v_{10}^2 - v_{20}^2}{2} + g(z_{10} - z_{20}) \tag{3}$$

Where:
E_h, specific hydraulic energy;
ρ, average water density of high- and low-pressure sections;
p_{10}, p_{20}, pressure of high-pressure section 10 and low-pressure section 20;

With specific mechanical energy and specific hydraulic energy, turbine hydraulic efficiency η_h can be determined by:

$$\begin{aligned} &\text{turbine}: \eta_h = \frac{E_m}{E_h} = \frac{P_m}{P_h} = \frac{\rho Q E_m}{P_h} \\ &\text{pump}: \eta_h = \frac{E_h}{E_m} = \frac{P_h}{P_m} = \frac{P_h}{\rho Q E_m} \end{aligned} \tag{4}$$

Turbine hydraulic efficiency η_m can be determined by:

$$\begin{aligned} &\text{turbine}: \eta_m = \frac{P_g / \eta_g}{P_m} = \frac{P_g / \eta_g}{P_g / \eta_g + P_l} \\ &\text{pump}: \eta_m = \frac{P_m}{P_g \cdot \eta_g} = \frac{P_g \cdot \eta_g - P_l}{P_g \cdot \eta_g} \end{aligned} \tag{5}$$

Where:
P_g, generator-motor active power;
η_g, generator-motor efficiency;
P_m, mechanical power of pump-turbine;
P_h, hydraulic power of pump-turbine;
P_l, mechanical loss of pump-turbine, mainly caused by bearing losses.

At last, pump-turbine efficiency η_t can be determined by:

$$\eta_t = \eta_h \eta_m \tag{6}$$

Definition and location of measuring quantities are shown in Figure 1.

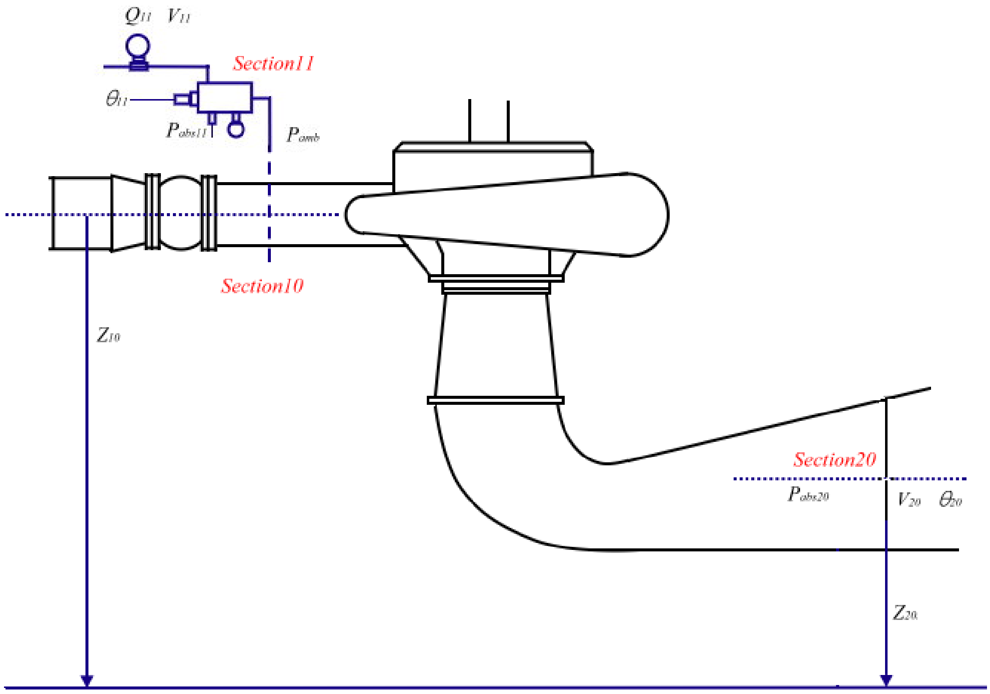

Figure 1: Locations of measuring quantities

As stated above, the key parameter is specific mechanical energy E_m to determine the turbine efficiency. Pressure, temperature and altitude can be measured at high-pressure section 11 and low-pressure section 20. Flow velocity v_{11} at high pressure section 11 can be directly measured in the sampling vessel [9]. So, the only remaining parameter to be determined is flow velocity v_{20} which is the mean velocity at low-pressure section 20. In other practice, a number of current-meters are arranged on the measuring frame to observe the velocity at low pressure section. However, due to unstable flow and velocity profile, it is difficult to get the correct mean flow velocity. In fact, velocity at low pressure section and turbine discharge can be worked out with other measured parameters. It is generally known that:

$$v_{20} = \frac{Q}{S_{20}} \tag{7}$$

Where:

Q, turbine discharge;

S_{20}, area of low-pressure measuring section.

Also, the corrective energy term of specific mechanical energy δE_m is usually presented as a function of only one variable as Q [10]:

$$\delta E_{\mathrm{m}} = f(Q) \tag{8}$$

To the measured pump-turbine, this function is specific and certain. With Equation (7) and Equation (8) substituted into Equation (2), a cubic equation with one variable for discharge shall be carried out expressing as Equation (9).

$$Q^3 - 2mS_{20}^2 Q - 2S_{20}^2 Qf(Q) + \frac{2S_{20}^2 P_{\mathrm{m}}}{\rho} = 0 \tag{9}$$

Where: $m = a\left(p_{\mathrm{abs11}} - p_{\mathrm{abs20}}\right) + C_P\left(\theta_{11} - \theta_{20}\right) + \frac{v_{11}^2}{2} + g\left(z_{11} - z_{20}\right)$.

Then turbine discharge can be worked out by Equation (9). In this paper, an improved procedure with an iteration way is proposed and more practical to perform at test site, which is shown in Figure 2.

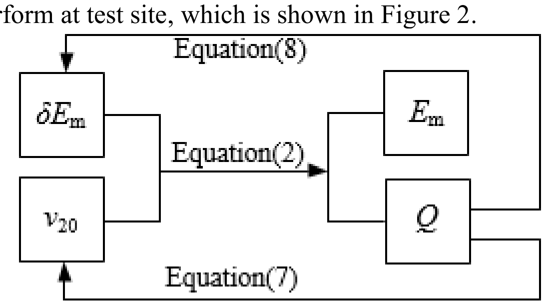

Figure 2: Iteration method to determine turbine discharge

Iterate for several times (usually 5~10) with initial $v_{20} = 0$ and $\delta E_m = 0$ until a convergence reached, then specific mechanical energy, turbine discharge and efficiency are worked out finally.

3. Results and discussion

Efficiency measurement is performed on a vertical pump-turbine with 600m rated head by thermodynamic method. Main turbine parameters are list in Table 1.

Table 1: Turbine parameters

Item	Unit	Detail
Type of pump-turbine	/	HLBD773-LJ-404
Rated net head	m	600
Max net head	m	643
Min net head	m	581
Rated speed	r/min	500
Rated discharge	m^3/s	57.05
Rated output	MW	306.1
Runaway speed	r/min	725

For pump-turbine, the water in the penstock flows along two directions as the turbine and pump operating conditions. And the sampling probe must satisfy the two operating conditions. As shown in Figure 3, two opposite inner channels are arranged in the probe to sample the water from both directions. A sampling vessel is arranged at high pressure section 11. Pressure p_{abs11}, temperature θ_{11} and altitude z_{11} are measured directly in the measuring vessel. Flow velocity v_{11} is measured by a magnetic flowmeter on the dewater pipe. The layout of sampling vessel at high pressure measuring section 11 is shown in Figure 3.

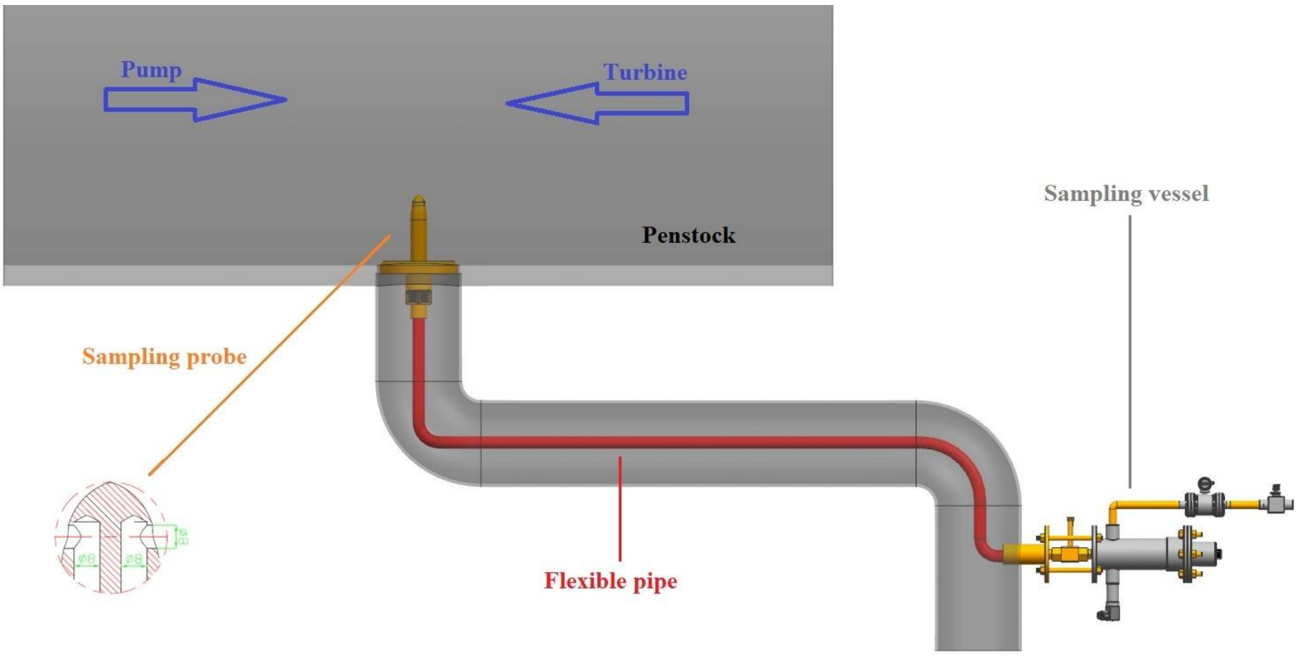

Figure 3: Layout of sampling vessel at high pressure measuring section 11

A measuring frame is located at low-pressure section 20 to measure the pressure p_{abs20}, temperature θ_{20} and altitude z_{20}. Due to temperature variation across the measuring section, measurement shall be made in at least four points. So, four inlet probes are arranged on the measuring frame to get the average temperature of the measuring section. The layout of measuring frame at low pressure measuring section 20 is shown in Figure 4. As shown in Figure 4, to satisfy the two directions of water flow from turbine and pump operating conditions, two opposite non-return valves are located at the start of inlet pipes, so the water flowing in the pipes may be leaded to the temperature sensor.

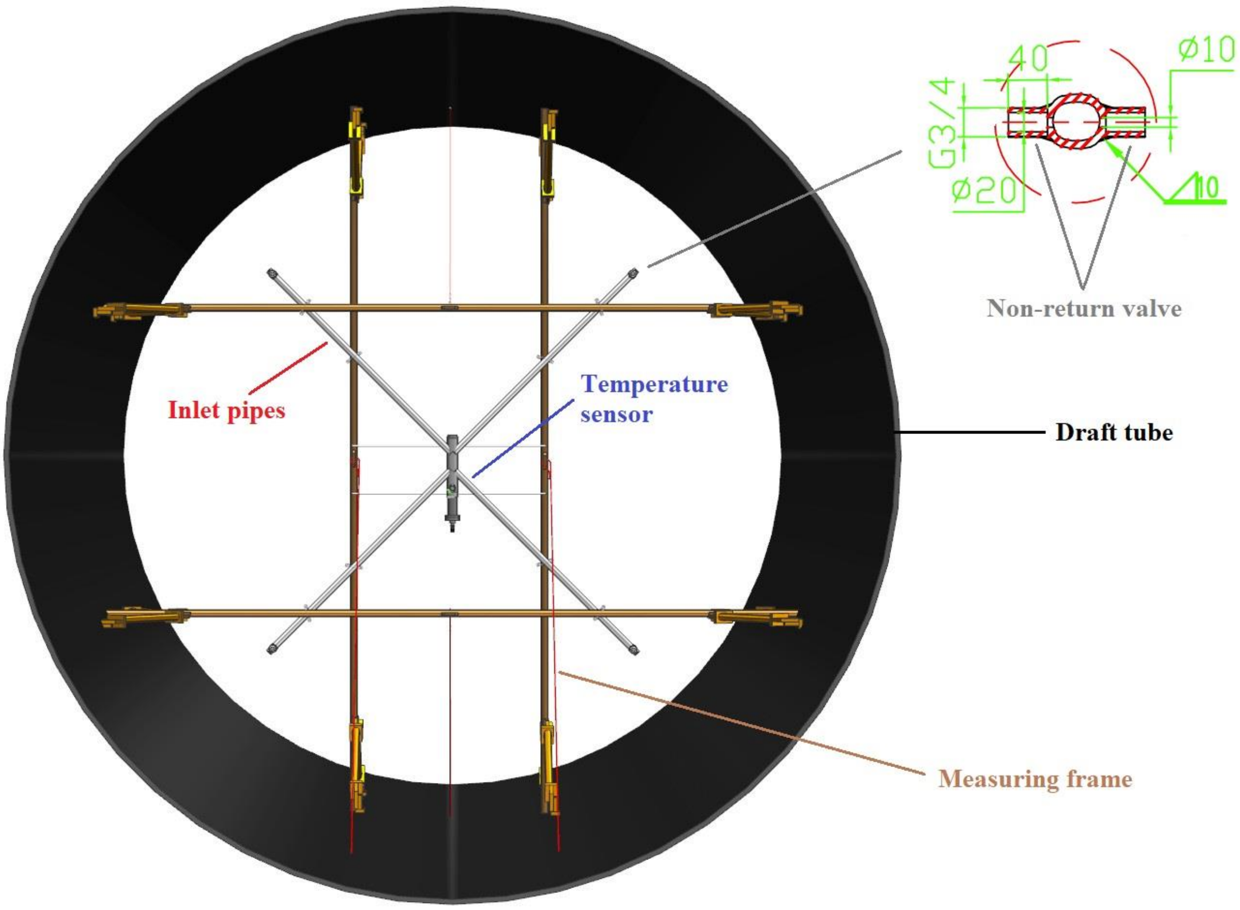

Figure 4: Layout of measuring frame at low pressure section 21

Design efficiency of turbine derives from model test results. Due to uncertain conditions in the flow passage of prototype turbine, measured efficiency is different with design values certainly. Measured turbine efficiency on rated net head is shown in Figure 5. As shown in Figure 5, measured turbine efficiency by thermodynamic method is higher than design values derived from model test when turbine mechanical output power is higher than 200MW.

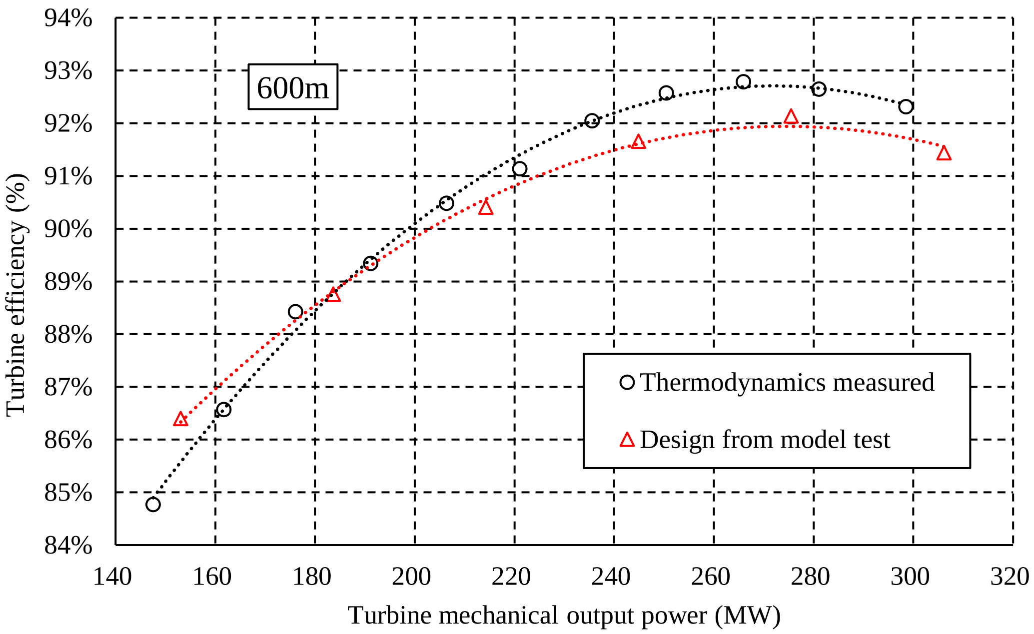

Figure 5: Comparison of thermodynamic efficiency and design from model test

Measured pump discharge by thermodynamic method is shown in Figure 6. As shown in Figure 6, at any specific input power of pump, measured pump discharge is lower than design values derived from model test.

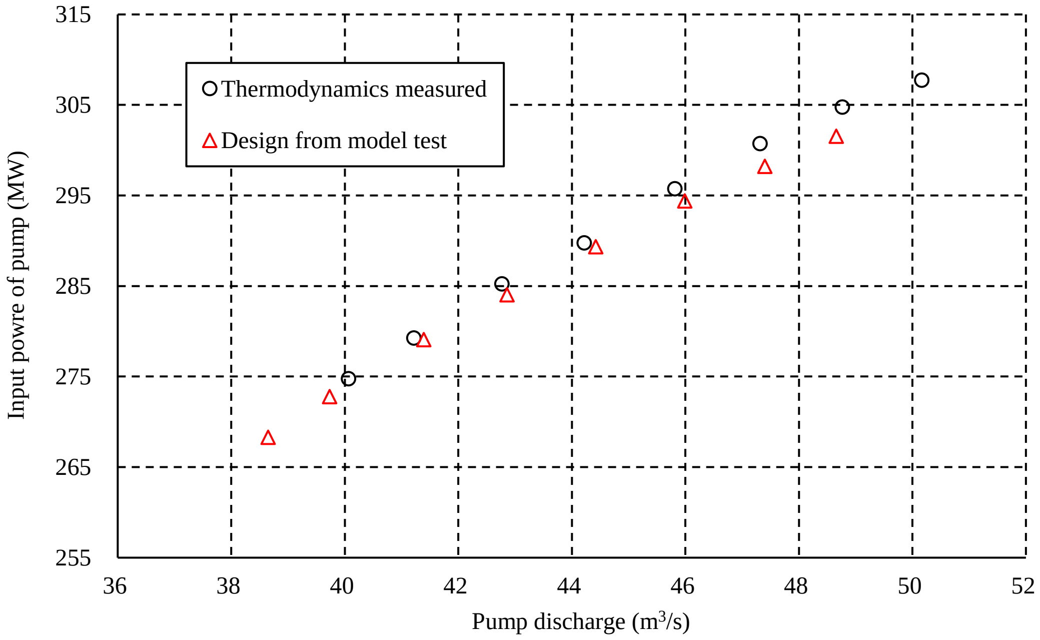

Figure 6: Comparison of thermodynamic discharge and design from model test

4. Conclusion

Efficiency measurement is performed on a vertical pump-turbine with 600m rated head by thermodynamic method in this paper. Special sampling probe and measuring frame are designed to satisfy both the turbine and pump operating conditions. An improved method to determine the turbine discharge is introduced, in which discharge may be worked out without need for flow velocity measurement at low pressure section. This method can avoid the uncertain impact from unstable flow and velocity profile. It is a practical way to determine turbine discharge of thermodynamic method. Test results show that specific mechanical energy, turbine discharge and efficiency are worked out after iteration several times. Determination of specific hydraulic energy, specific mechanical energy, discharge and efficiency of pump-turbine are discussed accordingly.

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