Efficiency measurement on horizontal Pelton turbine by
thermodynamic method

Dengfeng Cao, Ye Zhou, Luoping Pan and Junjie Wang
China Institute of Water Resources and Hydropower Research, A1, Fuxing Road,
100038, Beijing, China.
caodf1987@foxmail.com

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 horizontal Pelton turbine with 650m rated head and two jets by thermodynamic method in this paper. Determination of specific hydraulic energy, specific mechanical energy, discharge and efficiency of Pelton 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 measurement at low pressure section due to unstable flow and velocity profile [7] [8].

Efficiency measurement is performed on a horizontal Pelton turbine with 650m rated head and two jets 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. Determination of specific hydraulic energy, specific mechanical energy, discharge and efficiency of Pelton 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.

\[
E_m = a(p_{abs10} - p_{abs20}) + C_p(\theta_{10} - \theta_{20}) + \frac{v_{10}^2 - v_{20}^2}{2} + g(z_{10} - z_{20}) + \delta E_m
\]

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;
- \(\theta_{10}, \theta_{20}\), 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;
- \(\delta E_m\), 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. For Pelton turbine, low pressure section is at atmosphere pressure, so water variables (temperature and pressure) can be measured directly in the tailrace. Therefore, the practical expression of specific mechanical energy is:

\[
E_m = \bar{a}(p_{abs11} - p_{abs21}) + \bar{C}_p(\theta_{11} - \theta_{21}) + \frac{v_{11}^2 - v_{21}^2}{2} + g(z_{11} - z_{21}) + \delta E_m
\]

Where:
- Subscript 11 means high pressure measuring section 11 which locates at sampling vessel behind of main inlet valve of the unit, and 21 means low pressure measuring section 21 which locates at turbine tailrace channel.

Turbine input power, which presents as “specific hydraulic energy”, can be determined by measurement of pressure, velocity and altitude at high pressure section 10 and low pressure section 20:

\[
E_h = \frac{P_{10}}{\rho} + \frac{v_{10}^2}{2} + g(z_{10} - z_{20})
\]

Where:
- \(E_h\), specific hydraulic energy;
- \(\rho\), average water density of high and low pressure sections;
- \(P_{10}\), pressure of high pressure section 10;
- \(z_{20}\), average altitude of all contact points of the jet axis with the Pelton jet pitch diameter

With specific mechanical energy and specific hydraulic energy, turbine hydraulic efficiency \(\eta_h\) can be determined by:

\[
\eta_h = \frac{E_m}{E_h}
\]

Turbine hydraulic efficiency \(\eta_m\) can be determined by:

\[
\eta_m = \frac{\frac{P_g}{\eta_h}}{\frac{P_g}{\eta_h} + P_l}
\]

Where:
- \(P_g\), generator output active power;
\[ \eta_g, \text{ generator efficiency;} \]
\[ P_m, \text{ mechanical output of turbine;} \]
\[ P_l, \text{ mechanical loss of turbine, mainly caused by bearing losses.} \]

At last, turbine efficiency \( \eta_t \) can be determined by:

\[ \eta_t = \eta_g \eta_m \] (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 21. 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 \( v_{21} \), which is the mean velocity at low pressure section 21. 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. If enough velocity meters are used, the priority of thermodynamic method which doesn’t need to measure the discharge directly may not be presented. In fact, velocity at low pressure section and turbine discharge can be worked out with other measured parameters. It is generally known that:

\[ E_m = \frac{P_m}{\rho Q} \] (7)

\[ v_{21} = \frac{Q}{S_{21}} \] (8)

Where:
\[ Q, \text{ turbine discharge;} \]
\[ S_{21}, \text{ area of low pressure measuring section.} \]

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).

\[ Q^3 + mQ + n = 0 \] (9)

Where:
Then turbine discharge can be worked out by equation (9). In this method, an iteration way which is shown in Figure 2 is more practical to perform at test site.

![Figure 2. Iteration method to determine turbine discharge](https://example.com/figure2.png)

Iterate for several times (usually 5~8) with initial $v_{11} = 0$ 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 horizontal Pelton turbine with 650m rated head and two jets by thermodynamic method. Main turbine parameters are list in Table 1.

| Item                  | Unit | Detail                |
|-----------------------|------|-----------------------|
| Type of turbine       | /    | CJ102-W-207.2/2×20.2  |
| Rated net head        | m    | 650                   |
| Rated speed           | r/min| 500                   |
| Rated discharge       | m$^3$/s | 7.3                |
| Rated output          | MW   | 42                    |
| Runaway speed         | r/min| 915                   |
| Number of bucket      | /    | 19                    |
| Runner pitch diameter | m    | 2.072                 |
| Jet diameter          | m    | 0.202                 |

A sampling vessel is arranged at high pressure section 11. Pressure $p_{abs11}$, temperature $\theta_{11}$ 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](https://example.com/figure3.png)
A measuring frame is located at low pressure section 21 to measure the pressure $p_{abs21}$, temperature $\theta_{21}$ and altitude $z_{21}$. Due to temperature variation across the measuring section, measurement shall be made in at least six points. So six probes are arranged on the measuring frame to get the average temperature of the measuring section. And also, the measuring frame is installed at runner downstream with a distance of six times the runner diameter to make the water mixing adequately. The layout of measuring frame at low pressure measuring section 21 is shown in Figure 4.

Efficiency measurement is performed on this Pelton turbine by adjusting the output power from 0 to 42MW step by step to cover the total output range under rated net head. All the parameters are acquired synchronously. For Pelton turbine with two or more jets, the machine may runs under multi-setting of jets, which means different jets may produce different contribution to the turbine discharge. So in determining specific hydraulic energy according to equation (3), average altitude of all contact points of the jet axis with the Pelton jet pitch diameter $z_{20}$ is not constant which shall be determined by the actual opening of different jets as equation (10) shown.

$$z_{20} = \frac{j_1}{j_1 + j_2} z_{20-1} + \frac{j_2}{j_1 + j_2} z_{20-2}$$

(10)

Where:

- $j_1, j_2$: opening of jet 1 and jet 2 during operation;
- $z_{20-1}, z_{20-2}$: altitude of contact point of jet 1 and jet 2.

For Pelton turbine, during adjusting of jets operation mode (1 jet operation to 2 jets operation, opening adjusting of 2 jets, etc.), turbine output power may fluctuate and may not reach a table value [10]. Measurement points across these output range shall be excluded to get the correct efficiency curve of turbine. After measurement, efficiency curve of the test machine is shown in Figure 5.

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. As shown in Figure 5, for both 1 jet and 2 jets operation mode, measured efficiency is lower than design efficiency at small and large opening range. Maximum measured efficiency is higher than design values. Maximum efficiency tolerance of measured and design is 0.21%.

A multi-path ultrasonic meter has installed at the start of distributor pipe before test.Measured ultrasonic discharge is compared with that worked out by thermodynamic method. As shown in Figure 6, discharges measured by these two method are very close. Maximum difference of thermodynamic and ultrasonic discharge is 0.1m$^3$/s.
Figure 5. Measured efficiency curve of test Pelton turbine

Figure 6. Comparison of thermodynamic and ultrasonic discharge

4. Conclusion
Efficiency measurement is performed on a horizontal Pelton turbine with 650m rated head and two jets by thermodynamic method in this paper. Determination of specific hydraulic energy, specific mechanical energy, discharge and efficiency of Pelton turbine are discussed accordingly. In determining specific hydraulic energy, average altitude of all contact points of the jet axis with the Pelton jet pitch diameter is not constant which shall be determined by the actual opening of different jets. Also, to get the correct efficiency curve of turbine, measurement points during adjusting of jets operation mode shall be excluded. 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.
Acknowledgments
The paper is support by the IWHR Research & Development Support Program (HM0145B182017).

References
[1] IEC 60041 1991 Field acceptance tests to determine the hydraulic performance of hydraulic turbines, storage pumps and pump-turbines.
[2] L. Barbillon and A. Poirson 1920 Sur une méthode thermométrique de mesure du rendement des turbines hydrauliques, *La Houille Blanche*.
[3] G. Willim and P. Campmas 1954 Mesure du rendement des turbines hydrauliques par la méthode thermodynamique Poirson, *La Huille Blance*.
[4] F. F. Muciaccia 1998 Efficiency measurements on Pelton turbines with thermodynamic and acoustic methods *International Group for Hydraulic Efficiency Measurement*.
[5] O. G. Dahlhaug, T. K. Nielsen and B. Brandastro 2006 Comparison between pressure-time and thermodynamic efficiency measurements on a low head turbine *International Group for Hydraulic Efficiency Measurement*.
[6] H. Hulaas, T. Bryhni and O. G. Dahlhaug 2000 Multipoint thermodynamic measurements – a statistical approach to uncertainty levels *International Group for Hydraulic Efficiency Measurement*.
[7] G. Grego and F. F. Muciaccia 2004 Energy distribution analysis in a low head Francis turbine during thermodynamic efficiency measurements *International Group for Hydraulic Efficiency Measurement*.
[8] Thomas stauibli 2008 Efficiency differences of upper and lower injectors and scan of tailrace temperature distributions *International Group for Hydraulic Efficiency Measurement*.
[9] G. Alič and D. Dolenc 2018 Application of thermodynamic efficiency measurement with turbine cover drainage led into the draft tube cone *International Group for Hydraulic Efficiency Measurement*.
[10] Werner Schitter and Werner Mayr 2000 Thermodynamic efficiency measurement on a Pelton turbine before and after rehabilitation *International Group for Hydraulic Efficiency Measurement*. 