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Research of key technology for turbine efficiency measurement based on thermodynamics method

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Abstract. As it is difficult to get the absolute water discharge, from which we can calculate the turbine efficiency, the thermodynamic method is proposed as an effective and more precise method for higher than 100 meters' water head turbine. In which method, the water temperatures of inlet of spiral case and outlet of draft tube are measured and the flow discharge can be calculated according to the first law of thermodynamics. In the paper, with the practice and field test experience in several plants, some key technology and difficulties for thermodynamic method are discussed, which including advanced structure design and optimize for high pressure water sampling vessel, which can avoid the pipe crack or water leakage by reducing the connecting bolts and adding supporting bars, and a measuring frame in the draft tube flow channel, which using only one thermometer but can meet the requirement of IEC regulation; at last, for resolving the problem of flow velocity measurement in low pressure section, an iteration calculation method is brought out, and the field test data shows the method can get a good result for replacing the current meter method.

1. Introduction

Turbine efficiency is one of the most important technical factor for hydropower plant, especially in international hydraulic project, the check and measurement of turbine efficiency is an important part of unit commissioning and acceptance test, so it is significant to measuring the absolute efficiency of turbine.

The thermodynamic method is an effective and more precise method for higher than 100 meters' water head turbine. In which method, the water temperatures of inlet of spiral case and outlet of draft tube are measured and the flow discharge can be calculated according to the first law of thermodynamics[1].

The paper introduces the difficulties of turbine efficiency measurement by thermodynamic method, also gives the solution and advice for the problems, which can be good reference and guidance for later turbine absolute flow and efficiency measurement in other project or hydropower plant.

2. The thermodynamic method

2.1. Method principle

The thermodynamic method results from the application of the principle of conservation of energy (first law of thermodynamics) to a transfer of energy between water and the runner through which it is flowing.

In the case of actual machine operation, the energy per unit mass delivered to a turbine shaft may be determined by measurement of the performance variables (pressure, temperature, velocity and level) and from the thermodynamic properties of water. This exchange of energy will be referred to as "specific mechanical energy"[2].

In the case of ideal operation, i.e. frictionless flow (assuming identical pressure conditions at the inlet and at the outlet and an identical temperature at the inlet as in actual operation), the same application can be used for calculating the ideal energy per unit mass delivered to a turbine shaft. Such energy is dependent solely upon the properties of the water and the characteristics of the hydroelectric plant. It is referred to as "specific hydraulic energy".

In the actual operation, when the water passes through the turbine flow channel, it will produce a series of losses caused by friction, vortex, and flow separation and so on. All the losses will transfer to the thermal energy and make the water temperature difference between the turbine inlet and outlet section. The temperature difference is determined by the structure characteristics and work head of unit. Based on the temperature difference and water pressure, we can calculate the efficiency of turbine.

2.2. Calculation

In the case of actual machine operation, the energy per unit mass   delivered to a turbine shaft may be determined by measurement of the performance variables (pressure, temperature, velocity and level) and from the thermodynamic properties of water, and it can be calculated by the following equation[2][3][4].

$$E_h = \frac{(P_{abs1} - P_{abs2})}{\bar{\rho}} + \frac{V_1^2 - V_2^2}{2} + \bar{g} \cdot (Z_1 - Z_2) \tag{1}$$

Where,

$\bar{\rho}$, average water density of high and low pressure sections,

$\bar{g}$, average gravity at high and low sections,

P_{abs1}, P_{abs2} , water pressure in high and low pressure section,

V_1, V_2 , water velocity in high and low pressure section,

Z_1 , Z_2 , the level of high and low pressure measuring section.

$$E_m = \bar{a}\left(P_{abs1} - P_{abs2}\right) + \bar{C}_P\left(\theta_1 - \theta_2\right) + \frac{V_1^2 - V_2^2}{2} + \bar{g} \cdot (Z_1 - Z_2) + \delta E_m \tag{2}$$

Where,

θ_1 , θ_2 , water temperature of high and low pressure section,

$\bar{C}_P$, the average water specific heat capacity,

$\bar{a}$, the average adiabatic coefficient,

δE_m , the corrective energy term of turbine mechanical energy.

Normally, for the convenient of measurement, the water of high and low pressure measuring sections can be led into the sample vessel. So we can install a high pressure sample vessel on the inlet pipe of turbine, and measured the related parameters of it, such as the water pressure P_{abs11} , the water

temperature θ_{11}, the flow velocity V_{11}, the horizontal level of vessel Z_{11}, instead of measurement values in high pressure section of inlet pipe. Then, the specific mechanical energy E_m can be calculated by:

$$E_m = \bar{a}\left(P_{abs11} - P_{abs2}\right) + \overline{C_P}\left(\theta_{11} - \theta_2\right) + \frac{V_{11}^2 - V_2^2}{2} + \bar{g}\cdot\left(Z_{11} - Z_2\right) + \delta E_m \qquad (3)$$

Firstly, we can get the input power P of generator, with its output P_G and efficiency η_G, and get the turbine mechanical power P_m, then calculate the specific mechanical energy E_m with the parameters of sample vessel and low pressure measuring section. The flow discharge Q of turbine can be calculated with P_m and E_m, then the flow velocities in the high and low pressure section, finally, we can get the specific hydraulic energy E_h and hydraulic efficiency η_h, with turbine hydraulic efficiency η_h and turbine mechanical efficiency η_m, we can get the turbine efficiency η_t.

3. The design of measurement instruments

The measurement system consists of two parts, high pressure section and low pressure section, for the Francis turbine, which mean the inlet and outlet of turbine, also as entrance of pressure pipe and tailrace channel of draft tube[5][6]. The locations are shown in figure 1.:
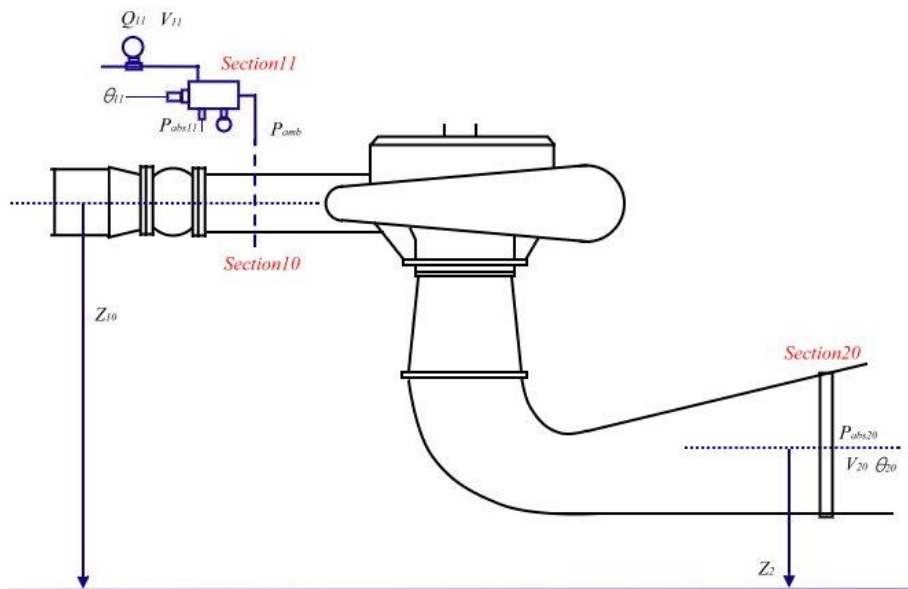

Figure 1. The measurement sections of thermodynamic method.

3.1. The high pressure measuring section

3.1.1. The common design of water sampling vessel. Due to the difficulties in measuring directly in the main flow, the quantities defining E_m can be measured in special designed water sampling vessel with taping for determination of temperature and pressure. By a water sampling probe, the water can be led to the water vessel through an insulated pipe to ensure that the heat exchange with exterior, which be estimated in accordance with the procedure clause 14.4.1.1 of IEC60041, and does not

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exceed the limit of corrections fixed in clause 14.6.3 of IEC60041.Refer figure 2. for measuring instruments sketch for high pressure section.
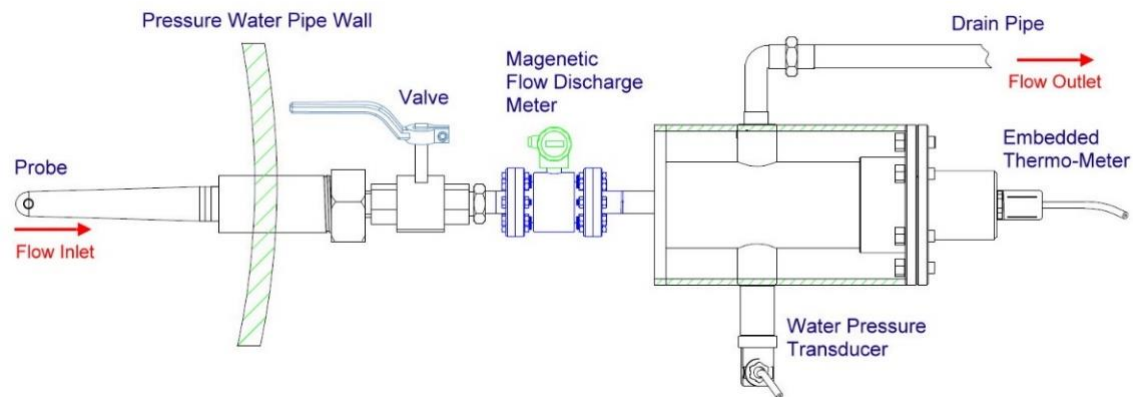

Figure 2. The design sketch of water sampling vessel with all sensors and accessories.

The common design of water sampling vessel shows it just assembles all the sensors and accessories together [5][6], but it cannot meet the requirements of IEC regulation, such as the requirement of magnetic flow discharge meter, as it needs to be installed in a long pipe with 10 times pipe diameter length before which, and 5 times pipe diameter length after[7][8].

Also, if we lengthen the connecting pipe of the flow discharge meter, it will be difficult to keep heat insulating effect. And at last, as the whole stainless steel sampling vessel with all accessories and being very heavy, the bolt connection between the pipes and valve will bear all the weight, so for the turbine inlet water pipe which can reach 3 to 5 MPa or much more water pressure, any crack or broken for connection or instruments will lead a very serious consequence.

3.1.2. The optimization of water sampling vessel. Considering the leakage of sampling vessel can be neglected, and the water flows through thermo-meter first, we can move the magnetic flow discharge meter to the end, which installed between the drain pipes, so we can lengthen the pipe before and after the flow meter and make the installation meets the requirement of flow measurement easily. Of course, the heat insulation for this part can be cancelled, the optimize design of water sampling vessel sees figure 3.
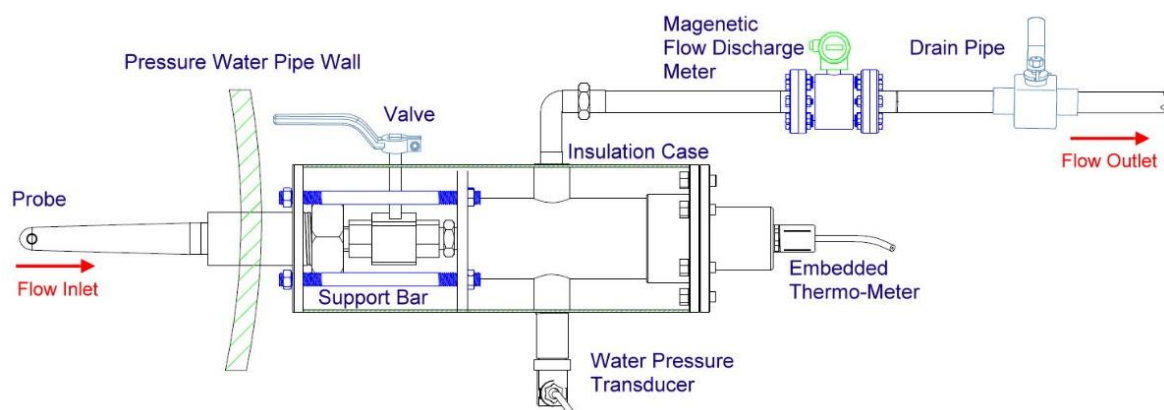

Figure 3. The optimization design of water sampling vessel with all sensors and accessories.

As the probe-fixing base being welded on the turbine pipe wall can support the heavy sampling vessel, four support bars are designed to connect the sampling vessel and fixing base, so the bars, not the valve connection take the force and weight stress.

Therefore, instead of pulling by a plastic rope or other temporary support racket, the design of support bars can improve the safety greatly, and has no influence for the heat insulation of sampling vessel, which can be fully covered by a cylinder case filling with heat insulation material.

3.2. The lower pressure measuring section

3.2.1. The requirement of IEC regulation. According to the Claus 14.5.1.2 of IEC 60041-1991, in open measuring section, exploration of temperature variation across the measuring section shall be made in at least six points; in closed measuring section, three or four points shall be made, and if there is a difference of at least 1.5% between the efficiency values at any two locations, proceed as described in IEC 60041-1991 14.5.4.

So, how to use fewer high accuracy and expensive thermos-meter to fulfil the requirement of IEC, is the difficulty for designing the measuring frame in the low pressure section.

3.2.2. The design of tail water measuring frame. We can gather water flow from six points to one, by an inter-connect pipe racket, and use only one thermometer to measure the average temperature, which can reduce the measuring error caused by temperature difference in different points. The design and picture for the tail water measuring racket and frame can refer to figure 4.

The measuring racket is made with three different length pipes, each has hole in both ends, and the water will flow together and flow out from the connecting centre outlet, where installing a high accuracy thermometer and water pressure transducer, for measuring the water temperature and pressure.

For comparing the efficiency result in different measuring points, during the test, we can change the whole racket position by rolling the hanging cable of the racket up and down, and measure the parameters in different position, but no more thermos-meters needed.
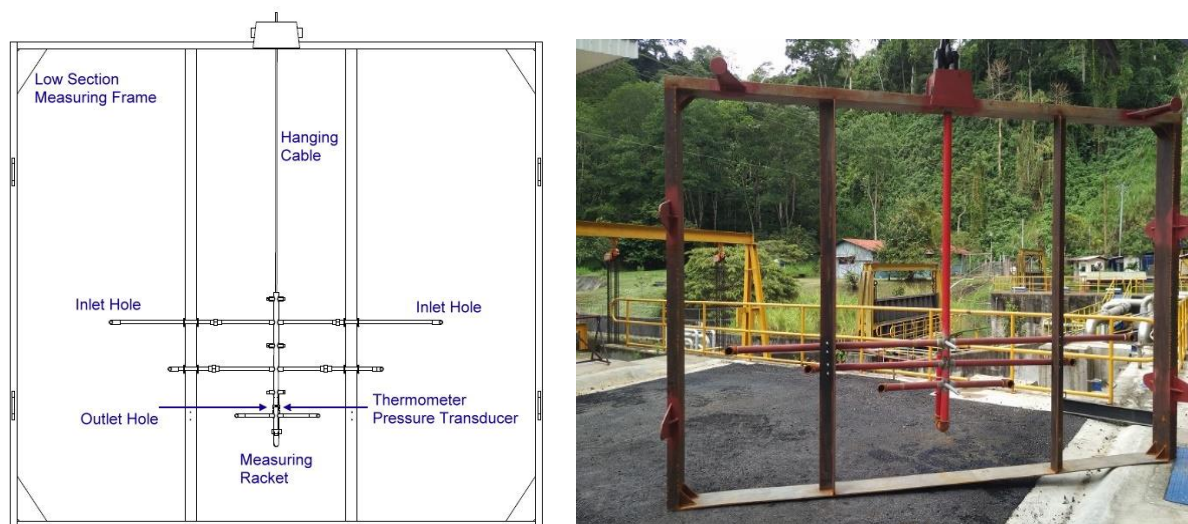

Figure 4. The design and picture for the tail water measuring racket and frame.

4. The flow velocity measurement of low pressure section

4.1. By flow current meter method

For measuring the flow velocity in tail water channel, one or two spiral blade flow meters usually can be equipped in the measuring frame, and measure the flow velocity at one or two points. But according to the requirement of chapter 'current-meter method' in IEC 60041-1991, considering the

distribution of flow state in the section and large measuring error, it is meaningless and not allowed to estimate the section flow velocity by so little current meters[9].

4.2. By iteration method
To the measuring parameters in high and low pressure section, the water pressure, water temperature and water level can be measured or calculated easily, the flow velocity through sampling water vessel also can be calculated with the magnetic flow meter.

As the flow discharge will be calculated by the parameters above, and the flow velocity can be calculated by the flow discharge and section area, so by iteration method, we can get the convergence value of flow discharge and velocity in low pressure section.

- First, assume the flow velocity in low pressure section as zero, we can calculate the specific mechanical energy E_m and mechanical power P_m by the equation (3), then the rough flow discharge Q_0,

- With Q_0 and low pressure section area, we can calculate the flow velocity V_{2_1}, then we can repeat the step one, and get the second flow discharge Q_1,

- Then repeat the step two, we can get the flow velocity V_{2_2}, then get the third flow discharge Q_2.

Through the iteration calculation two or three times, we can find the flow velocity and discharge both reach to the convergence values. A flow velocity calculation example by iteration in a past test is listed in table 1.

Table 1. A flow velocity calculation example by iteration.

Iteration Times	Turbine Flow Discharge (m^3/s)	Flow Velocity in Low Pressure Section (m/s)	Error
1	17.6030	0.00000	-100%
2	17.6223	2.25679	-0.1102%
3	17.6224	2.25927	-0.0002%
4	17.6224	2.25928	0.0000%

Form the Table 1, it can be concluded that by iteration method, the flow discharge and velocity in low pressure section will converge in very few times, and the method without installing any current meters in low pressure section can meet the actual needs.

5. Conclusion
With the practice and field test experience in several plants, some key technology and difficulties for thermodynamic method are discussed, which including advanced structure design and optimize for high pressure water sampling vessel, which can avoid the pipe crack or water leakage by reducing the connecting bolts and adding supporting bars, and a measuring frame in the draft tube flow channel, which using only one thermometer but can meet the requirement of IEC regulation; at last, for resolving the problem of flow velocity measurement in low pressure section, an iteration calculation method is brought out, and the field test data shows the method can get a good result for replacing the current meter method.

However, the thermodynamic method is effective for measuring the absolute efficiency of turbine with high work head, but we still need do more researches for improving the heat insulation and structure strength of water sampling vessel, and increase the test accuracy by optimizing the calculation of correction items for specific mechanical energy.

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