Experience Measurement of Winter-Kennedy method on low head tubular turbine units

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Abstract. With large development of renewable energy, especially the low head hydraulic power stations, specifications of the turbines have been got more and more attentions. The discharge, which is one of the most important parameters relative to unit performances, is difficult to be determined according to the passage layout. In this paper, applying “Winter-Kennedy” measurement method though modification and comparison with test and simulation, characteristics and coefficients of turbine units, derived from different pressure at certain locations, are calibrated and established. After further verification, it will of great help to confirm the relationship of unit output, water head and hydraulic efficiency, as well as optimal dispatching and stable operation of hydropower stations.

1. Introduction

With continuously increasing demands on energy that is the lifeblood of worldwide economic and social development, and great emphasis on preventing against the dangers of global environmental impacts, hydropower, considered to be one of the main renewable energy resources [1-2], provides a potential opportunity to deal with alternative energy generation and growing energy consumption and stimulate worldwide development, which is substantially playing a greater role in generating electricity than that of any other renewable energy technology. Since the deployment of large/mid-sized hydropower projects has been already and more or less close to a higher and maximum exploitation and utilization level and meanwhile its sustainability usually comes up to be a major questioned barrier as a result of the long and large cost of the dams as well as the impacts on the environment, to date, with the advantages of scale (i.e., small), capital cost (i.e., little), deployment time (i.e., short), and environmental compatibility (i.e., low impact), most published literature focuses mainly on low head hydropower technologies that use low hydraulic heads between 2 m and 15 m, which have greater capacity to contribute to rural electrification and make instant impact on the replacement of fossil fuels [3].

For low-head head hydropower, compared with high-head, large- diameter units, the operating head is low, and the flow velocity through turbine passages is relatively low, of which the effect on the turbine performances is still not clear whether it is positive or negative [4-5], so is water level, gravity, surface vortex, etc.. The strong surface vortex especially can entrain the air, and it would cause non-uniform intake flow characteristics. The non-uniform influx causes irregular load on the turbine runner and increases vibration caused by additional radial forces [6]. In view of the application scenarios,
Froude number is quite low, which is defined as $Fr = \frac{U}{(gD)^{0.5}}$, so that the gravity force also proves to be another main parameters governing the flow field, which induces vertical pressure gradients in the turbine runner, and influences the cavitation performance especially for axial-type hydraulic turbines. Besides, Ahn [7] investigated numerically Coriolis effects on turbine performances, and found out that the Coriolis Effect increases the flow non-uniformity in the turbine intake at low Rossby number, which could influenced turbine performances. Same to CFD simulation. Zhou brought out a novel methodology through the simulation and model test to predict the hydraulic specifications like efficiency, output and cavitation properties, with further adaptation to execute the hydraulic, dynamic and stability analysis [8]. With regards to the experimental achievements, most researchers have been paid attention to the offshore turbines, such as current horizontal-axis turbines, vertical-axis turbines and WOC that focus on the capacity, inlet angle, velocity distribution and so on. Guo [9] performed scale experiments on tidal turbine and showed that “The wave induced torque and thrust tend to a fixed value when the incident wave length is much longer than the water depth, which provides an approximate assessment of the surface wave effects on tidal turbines.” Zang [10] established tests with Acoustic Doppler Velocimeter (ADV) to indicate mean wake and Gaussian distribution are consistent with waves on the wake recovery, turbulence intensity is affected by the wave height for the upper region, and the influence of the wave period was greater for the integral time scale than for the wave height at the far-wake region. Nevertheless, study on the internal flow passage by means of model test and site measurement seldom has been published, considering the complex operation conditions and unsuspected environmental factors.

Therefore, in order to accurately evaluate the prototype performances not only by the simulation but also through the practical application site test, the suitable measurement method should be met with the demands for low head hydropower, together with “run-of-river” units, offshore turbines and low-head pumps. The objective of this paper is to give out an available method for monitoring the flow discharge along the passage. And then, it is evaluated with CFD results and test data in a power station. In addition, the proposed method is discussed and compared with different measurement section parameters in order to provide a foundation for further predict unit performances under the interaction and the transient change.

2. Flow measurement method

Flow discharge is the essential and mainly important parameter of hydraulic machinery performance tests under field conditions which is one of the most difficult measurement tasks to be achieved in order to investigate water turbine efficiency in hydropower stations, especially complex in water power plants with no access to the flow system from outside, and no suitable measurement installations prepared during construction.

In recent years, more and more various methods of flow discharge measurement [11] have been developed and turned out to be a great success when applied in practical use, such as:

1. Ultrasonic Flowmeter-flow velocity measurement, as shown in Figure 1. Piezocrystals are located a distance apart on a line passing obliquely through the pipe central line. An ultrasonic wave pulse sent from a transmitter is received by the other detector at seconds later, exchanging the functions by the send–receive switch, the mean velocity will be obtained.

2. Magnetic Flowmeter-flow velocity measurement, as shown in Figure 2. Referring to Faraday's law, when a conducting fluid with flux density $B$ flows normal to the flow direction, an electromotive force $E$ proportional to the mean flow velocity $v$ is induced in the liquid, which permits computation of the volume flow rate $Q$ irrespective of the viscosity, specific gravity, pressure and Reynolds number of the fluid.

3. Coriolis Flowmeter & Thermal Mass -mass flow rate measurement in Figure 3, depending largely on the device accuracy, with rectification oscillation detected by a pair of the electromagnetic pickoffs or temperature difference converted into electric voltage in the bridge circuit is proportional to mass flow rate.
(4) Gibson method—pressure-time method, recognized by international standards[12-13] and American standard [14], utilizes the water hammer phenomenon, which is primary measurement method particularly used in large-scale hydropower systems equipped with long pipeline derivation as shown in Figure 4.
In order to execute the performance analysis of low head hydropower, there is urgent need to introduce available flow rate measurement method. Consulting to the relevant studies, Winter-Kennedy method for index test is brought out. As stated in the followings, based on free vortex theory and Bernoulli equation together with the assumption of incompressible fluid in cylindrical coordinates, inviscid steady flow and negligible radial and vertical components.

By integrating equations, we can get the flow rate, that is:

\[
Q = K \times AP^n
\]

where \( Q = u_A A \) and \( n \) is a given exponent [15]. Thus, the flow rate of low head hydropower can be measured by monitoring the pressure difference at set sections along the passages together with the calibration of W-K coefficients to be determined numerically or/and experimentally.

3. Application Investigation with Winter-Kennedy method

To confirm the generality and practicability of Winter-Kennedy method in low head hydropower, both CFD and field test of a low head prototype tubular are carried out to look into the different calibration ways of W-K coefficients and various effect on the flow rate, so as to offer good evidence that the corrected method are more suitable for the low head turbines.

3.1. Numerical simulation

According to the layout of the flow passage property, the calculation model is established, as shown in Figure 7, which consists of so-called spiral casing (SP), guide vane (GV), runner chamber (RV) and draft tube (DT), and the parameters relative to the performed prototype are demonstrated in Table 1.
Figure 7. Sketch of low head hydropower turbine

Table 1. Parameters of the prototype turbine

| Unite type          | D(mm) | GV(\textdegree) | RV(\textdegree) | H(m)   |
|---------------------|-------|-----------------|-----------------|--------|
| Bulb tubular turbine| 4300  | 16              | 3               | 2.50~7.12 |

After computation domain discretization, a principle by the governing equations, together with the SST-CC turbulence model, the CFD simulation is executed by use of ANASYS tools [8, 16]. Reference to the international standards and the test point located in the field test, there are four pressure monitoring section as well as the points set in the CFD simulation, of which the locations are the same with $P_0$, $P_1$, $P_2$ and $P_5$, as set in Figure 9. To compare the pressure and the discharge specifications with the measurement at various operation conditions, steady-state simulation is performed of which some results are listed in Table 2.

Table 2. Characteristics of the prototype turbine by CFD

| No. | $Q^*$(-) | $P_0-P_2$(Pa) | $P_1-P_2$(Pa) | $P_0-P_5$(Pa) |
|-----|----------|----------------|----------------|----------------|
| 1   | 0.515167 | 3404.243       | 3450.024       | 77776.15       |
| 2   | 0.529507 | 3567.003       | 3581.047       | 77802.75       |
| 3   | 0.624992 | 4662.309       | 4634.238       | 77979.34       |
| 4   | 0.642496 | 4884.299       | 4857.621       | 77925.37       |
| 5   | 0.729219 | 6066.473       | 5968.227       | 77835.06       |
| 6   | 0.746525 | 6266.885       | 6190.977       | 77750.11       |
| 7   | 0.849879 | 7753.702       | 7620.547       | 77387.9        |
| 8   | 0.876222 | 8126.615       | 7988.951       | 77319.94       |

Note: Discharge ratio $Q^*=Q/Q_0$, where $Q_0$ refers to rated discharge of the turbine.

Reference to the IEC standard [12, 13], Winter-Kennedy method could be applied for the tubular turbines when pressure difference measurement suitably located points as shown in Figure 8. Similar to the standard requirements, the W-K coefficients calibration used in the objective turbine should be determined by the differential pressure between the cross section $P_1$ and $P_2$, and on basis of the CFD results stated above, the linear fitting analysis is implemented among the data as shown in Figure 9. As can be found from the figure, it is clear to indicate the relationship curve between flow discharge and pressure difference exhibits a very good linear relationship with an error 1.74%, which further validates the availability of Winter-Kennedy method.
3.2. Site Field Test

As for case simulation to be further checked, the site field test designed for the objective unit is also carried out and the layout of the pressure test section is shown in Figure 10. Besides the pressure, other parameters relevant to the hydraulic specifications, such as the torque, rotation speed \(\omega\) and output are involved during the process for further analysis between CFD simulation and test data.

![Figure 8](image8.png)

**Figure 8.** Location for differential pressure method of flow rate measurement

![Figure 9](image9.png)

**Figure 9.** Flow Coefficient curve with Winter-Kennedy method \((P_1-P_2)\)

![Figure 10](image10.png)

**Figure 10.** Pressure monitoring section along the passage
To make test results scientific and reasonable, the test procedure and the data processing abides by IEC code 60193-1999 standard and relative parameters such as $H$, $P_t$ and $Q$, which will be picked out for comparison, are acquired according to the following equations:

$$ H = V_1 - V_2 + \frac{P_1 - P_2}{\rho g} + \frac{V_1^2 - V_2^2}{2g} $$

(3)

$$ V_1 = \frac{Q}{A_1}, \quad V_2 = \frac{Q}{A_2} $$

(4)

$$ P_t = P_1 \left( \frac{H_1}{H_n} \right)^{\frac{3}{2}} $$

(5)

$$ Q = Q \left( \frac{H_1}{H_n} \right)^{\frac{1}{2}} $$

(6)

Once the W-K coefficients are determined by a suitable and correct measurement of pressure difference, Winter-Kennedy method can be applied for an absolute flow condition to dig into the performance characteristics of the tested turbine, of which the efficiency and discharge curves are shown in Figure 11.

![Figure 11. Specification of hydraulic performance (P1-P2)](image)

3.3. Verification and Discussion

For the deep validation, Winter-Kennedy method with various pressure difference sections is put into practice to compare with the discrete data points. According to the former study, the streamline along the passage as shown in Figure 12 gives out a guiding proof that differential pressures of $(P_0-P_1)$ and $(P_0-P_2)$ are basically met with the inviscid and non-vortex assumption. Taking the case of $(P_0-P_2)$, the corresponding parameters are obtained by the same method, and the result is listed in Figure 13 which comes up to be linear relationship with an error 2.11%. Contrasting with the hydraulic performance for deep analysis, $P_g^*-Q^*$ and $P_g^*-\eta^*$ curves are drawn as shown in Figure 14, where output ratio $P_g^*=P_g/P_r$ and relative efficiency $\eta^*=\eta/\eta_{max}$.

![Figure 12. Streamline along the flow passage](image)
4. Conclusion

In this paper, based on the CFD simulation and the site test of a low-head tubular turbine, Winter-Kennedy method aimed for index test on the performance prediction is given out for flow rate measurement and through the W-K coefficient calibration analysis and comparison with different ways to be utilized the followings can be found:

(1) Besides for index test, Winter-Kennedy method, once the W-K coefficients calibration is checked, turns out to be a reliable and effective way for an absolute flow rate measurement when located between suitable differential pressure monitoring sections. Meanwhile, through the feedback confirmation, this method equipped in real application displays strong robustness and practicability;

(2) For further verification, two types of pressure difference are conducted and though the contrast and analysis it is noticed that \((P_r-P_2)\) and \((P_t-P_2)\) are both proportional to flow discharge along the
turbine passage, and yet the flow rate derived from \((P_0 - P_2)\) is higher than that from \((P_1 - P_2)\), and the error between two types of pressure difference is larger especially for small flow situations while it decreases with the flow discharge increment.

As stated in in the sub clause 4.8.1 IEC60193 “the index test in the model can never be a substitute for an absolute discharge measurement at the prototype”, especially for low head hydropower, flow conditions, Reynolds number, and wall roughness…are not constant between model and prototype. For erroneous results analysis and widespread utilization, it is of critical necessity to promote CFD study on oscillating flow and velocity change conditions at various loads as well as flow and pressure measurement like LDV and phase-resolved mechanism tools.

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