Analysis on Energy Loss Characteristic of a Bidirectional Tubular Turbine Based on Entropy Generation Theory

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Abstract. To obtain the external characteristic parameters and the distribution of hydraulic loss, ANSYS CFX code is used to for numerical simulations of a tidal bidirectional tubular turbine under positive and reverse conditions. The method of entropy generation analysis is used to obtain the energy loss in the unit and its local entropy generation rate. Besides, the influence of the shaft inclination in the guide vane on the tubular turbine is explored. The results show that there is a certain connection between the traditional hydraulic loss analysis and entropy generation analysis. Entropy generation could be adopted for the measurement of hydraulic loss with its distribution. The total entropy production is dominated by the runner under positive optimal condition, while the ones in the runner and the intake are the highest under reverse optimal condition. In addition, the greater the shaft inclination angle of the guide vane, the larger the total entropy production on the blade surface of the runner under the positive condition.

1. Introduction

Tubular turbines have merits of high performance, high specific speed and small hydraulic loss. As the development of medium and high head water resources is exhausted, the use of low-head resources has received more attention. Therefore, tubular turbines have increasingly become the key research of scholars because of their low head and wide operating ranges [1]. Thaithacha and Udomkiat [2] predicted the unstable cavitation of the runner blades in the bulb turbine, and found that the fluctuation of the torque is the main reason reducing the life of units. Duquesne et al. [3-4] made an experimental study on the hydraulic loss and flow separation in draft tube of one bulb turbine, and described the effect of flow separation on the unit’s performance. For studies in energy loss, both model tests and numerical simulations have certain limitations. In recent years, some scholars have linked energy loss with entropy generation which can be applied accurately on the location and magnitude of energy loss. Li et al. [5] presented that the hydraulic loss in key components was one of the main reasons for pump-turbine’s hump behaviour with hysteresis. Feng et al. [6] investigated energy loss of each flow component in a centrifugal pump during accidental power failure based on entropy generation theory. Shehata et al. [7] found that the guide vane with different shapes and different openings played an important role on units’ entropy generation rate.

Compared with the traditional method of energy loss, the entropy generation theory has great advantages. It is, however, currently rarely used in hydraulic turbines, especially in tubular turbines. Therefore, taking a power station’s tidal bidirectional tubular turbine as an example, the energy loss in positive and reverse conditions is analysed and evaluated based on the entropy generation theory. The influence of shaft inclination angles for guide vane on the energy loss of the unit under positive and reverse
conditions is studied, which provides a reference for the optimal design of the bidirectional tubular turbine under positive and reverse conditions.

2. Numerical Methodology

2.1. Geometric Model
The bidirectional tubular turbine model of a tidal power station is adopted as the object shown in Figure 1, including the intake, guide vane with 16 vanes, runner with 4 blades and draft tube. The diameter for the runner is 0.35m. Moreover, Table 1 shows parameters for the turbine on positive and reverse optimal conditions.

2.2. Meshing
Computational meshes with hexahedral structure are generated for the flow domains of three-dimensional geometry by ANSYS ICEM. The mesh views of different flow components are presented in Figure 2. After verification of grid independence with the efficiency, the number of grids was finally applied to be 5.32 million.

2.3. Boundary Condition Setting
The commercial software ANSYS CFX was adopted to calculate the flow in tidal bidirectional tubular turbine under positive and reverse optimal conditions. The shear stress transport (SST) k-ω turbulence model was used. The inlet with outlet boundary conditions were both specified as mass flow rate. Solid walls were set to no-slip boundary conditions.

3. Entropy Generation Theory
The entropy generation rate consists of two parts: direct dissipation caused by time-averaged motion and turbulent dissipation due to pulsating velocity:
\[
\dot{S}_n^D = \mu \frac{T}{\tau_w} \left[ \left( \frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right)^2 + \left( \frac{\partial u}{\partial x} + \frac{\partial w}{\partial y} \right)^2 + \left( \frac{\partial v}{\partial x} + \frac{\partial w}{\partial y} \right)^2 \right] + 2 \mu \frac{T}{\tau_w} \left[ \left( \frac{\partial u}{\partial x} \right)^2 + \left( \frac{\partial w}{\partial x} \right)^2 + \left( \frac{\partial v}{\partial y} \right)^2 \right] \tag{1}
\]

\[
\dot{S}_n^T = \frac{\mu_{eff}}{T} \left[ \left( \frac{\partial u'}{\partial y} + \frac{\partial v'}{\partial x} \right)^2 + \left( \frac{\partial u'}{\partial x} + \frac{\partial w'}{\partial y} \right)^2 + \left( \frac{\partial v'}{\partial x} + \frac{\partial w'}{\partial y} \right)^2 \right] + 2 \frac{\mu_{eff}}{T} \left[ \left( \frac{\partial u'}{\partial x} \right)^2 + \left( \frac{\partial w'}{\partial x} \right)^2 + \left( \frac{\partial v'}{\partial y} \right)^2 \right] \tag{2}
\]

where \( S_n^D \) and \( S_n^T \) are the direct and turbulent dissipation entropy production rate, respectively. \( \bar{u}, \bar{v}, \bar{w}, u', v', w' \) are three average pulsating velocity components. \( T \) is temperature, \( \mu \) is dynamic viscosity, \( \mu_{eff} \) is effective dynamic viscosity.

To reduce the error near the wall, the entropy production near the wall is calculated as follows [8]:

\[
\dot{S}_w = \frac{\tau_w \cdot u_p}{T} \tag{3}
\]

where \( \tau_w \) is wall shear stress, \( u_p \) is average velocity vector at the first layer of the grid near the wall.

The local entropy production rate is the sum of \( \dot{S}_n^D \) and \( \dot{S}_n^T \). The total entropy production is the sum of direct dissipation, turbulent dissipation and wall entropy production.

### 4. Results and Discussion

Table 2 shows the external characteristics of the bidirectional tubular turbine in positive and reverse optimal conditions. As shown in table, the efficiency of the positive condition 85.3% is higher than that of the reverse condition, so is the power. It may be because the flow enters the runner without circulation, leading to a lower flow utilization rate on reverse condition without rear guide vanes.

| Parameters | Positive optimal condition | Reverse optimal condition |
|------------|---------------------------|--------------------------|
| Efficiency (%) | 85.6 | 78.9 |
| Power (kW) | 23.38 | 19.12 |

Table 3 shows the distribution of hydraulic loss and total entropy production for components. It is found that the distribution for hydraulic loss and total entropy production of each component are similar, the runner accounting for the main part on positive condition and the runner with intake dominating on reverse condition.

| Parameters | Optimal condition | Intake | Guide vane | Runner | Draft tube | Sum |
|------------|-------------------|--------|------------|--------|------------|-----|
| Hydraulic loss (m) | Positive | 0.03 | 0.12 | 0.46 | 0.12 | 0.73 |
| | Reverse | 0.46 | 0.07 | 0.51 | 0.02 | 1.06 |
| Total entropy production (W/K) | Positive | 5.73 | 0.68 | 7.13 | 0.28 | 13.82 |
| | Reverse | 5.73 | 0.68 | 7.13 | 0.28 | 13.82 |

Figure 3. Distribution for total entropy production and hydraulic loss of each component.
Figure 3 depicts proportions for total entropy production and hydraulic loss for components. Proportions for total entropy production and hydraulic loss in each component are approximately same with a maximum difference of 10%, especially on reverse condition. Therefore, the entropy generation theory could be adopted for evaluating the quantity and distribution of hydraulic loss. Figure 4 presents the distribution for local entropy production rate at pressure and suction surfaces under the positive and reverse conditions. For both conditions, the local entropy production rate gradually increases from inlet to outlet for pressure surfaces, while high entropy production rate appears at the leading edge for suction surfaces near shroud. Particularly, the area for high entropy production rate increases obviously under reverse condition.

![Figure 3](image1.png)

**Figure 3.** Proportions for total entropy production and hydraulic loss for components.

Figure 4. Distribution for local entropy production rate of runner blade: pressure side (left) with suction side (right).

Figure 5 shows the surface pressure distribution for the runner blade along streamline. Under both conditions, the pressure difference increases from span=0.1 to 0.9 near the blade leading edge which means the strong power conversion at span=0.9. In addition, the minimum pressure of blade’s suction surface under positive condition is lower, which is more prone to cavitation.

![Figure 5](image2.png)

**Figure 5.** Surface pressure distribution on runner blade.

Figure 6. Local entropy production rate in draft tube under positive condition.

Figure 7. Local entropy generation rate in intake under reverse condition.
Figures 6 and 7 show the distribution for local entropy production rate at draft tube under positive condition and intake under reverse condition, respectively. The high entropy production rate is observed at the draft tube inlet near hub under positive condition, while it occurs at intake near the hub under the reverse condition. In addition, large entropy production rate close to the wall or hub reduces from the inlet to outlet.

The shaft inclination angle of the guide vane is the angle between the center axis of the guide vane and the centerline for the main shaft of the turbine, denoted as $\alpha$ in Figure 8. The influence of the shaft inclination angle of the guide vane (65°, 75° and 85°) on the flow loss inside the turbine based on entropy generation is explored.

The total entropy production under the reverse condition is significantly higher than that of the positive condition shown in Figure 9, decreasing with increase of the shaft inclination angle of the guide vane under both conditions. It means the hydraulic loss is gradually reduced. Compared to the larger variation from 65 degrees to 75 degrees, the total entropy production hardly changes after 75 degrees.

Figure 10 shows the distribution for local entropy production rate at runner’s suction surfaces under the positive optimal condition. As the shaft inclination angle of the guide vane increases, the overall local entropy production rate gradually increases. The area for high values at the inlet close to the shroud increases significantly, and the flow loss gradually increases.
Figure 11 describes distributions for local entropy production rate in midsection of draft tube on positive condition. As the shaft inclination angle for the guide vane increases, the local entropy production rate at inlet near hub hardly changes, while the entropy production rate near wall gradually decrease.

5. Conclusion

The internal flow loss of a bidirectional tubular turbine is analyzed based on the entropy generation theory. Major conclusions are drawn as follows.

(1) The results obtained by the traditional hydraulic loss analysis and entropy generation analysis are roughly the same with a certain correlation, so the loss in the internal flow can be evaluated and analyzed by entropy generation theory. The total entropy production of the runner accounts for the main part on positive condition and that of the runner with intake dominates on reverse condition.

(2) Under both conditions, the local entropy production rate at inlet for runner suction surface near shroud is larger. The local entropy production rate at inlet for draft tube near hub and the wall in the positive condition is relatively large, while it is higher at intake near the hub under the reverse condition.

(3) As the shaft inclination angle for the guide vane increases, total entropy production for the flow channel gradually decreases under both conditions, indicating that the energy loss is gradually reduced. The local entropy production rate at inlet for runner suction surface near shroud, however, gradually increases under the positive condition with decreasing in the draft tube.

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