Investigation on Runaway Process in Power Generation Device: Tubular Turbine Based on IB-LBM Method

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Abstract. The immersed boundary lattice Boltzmann method (IB-LBM) was applied to numerically simulate the runaway process of tubular turbines with the influence of the free surface of upper and lower reservoirs. First, the accuracy of the IB-LBM method was verified, and then the external performance and internal flow characteristics of units during runaway process were studied. The results show that the gravity causes uneven pressure distribution at inlet of the turbine with considering the influence of the free surface of the reservoirs, resulting in complicated flow pattern, which cannot be ignored in the study. In the course of runaway, low-pressure area of draft tube changes periodically with a certain degree of cavitation occurring on pressure and suction surface of the blades, which threatens the overall operation stability of the unit.

1. Introduction
With the gradual saturation of the development of medium- and high-head hydraulic resources, the low-head hydraulic resources have become the focus of attention [1]. As an ideal power generation device for the low-head hydraulic resources, the tubular turbine has superior hydraulic performance and extremely high economic benefits. It needs, however, frequent start and stop and changing work conditions during the power generation process, causing severe pressure pulsation and vibration, which will threaten the stability of the unit. Therefore, to make sure the stable operation of hydropower stations with units’ safety, it is important to study the transient flow characteristics of tubular units. Cherny [2] and Li [3] carried out a numerical investigation on flow characteristics inside the turbine during runaway process, and obtained the evolution of vortex and pressure fluctuation in the draft tube. Xia et al. [4-5] applied the immersed boundary method in the 3D CFD simulation of bulb tubular turbines and presented the evolution of the parameters including pressure pulsation, rotational speed, torque, axial thrust and the internal flow pattern. Zhou et al. [6] found that closing the blades during the runaway process of a Kaplan turbine can reduce the velocity with pressure pulsation and improve flow pattern of the draft.

In summary, CFD can be applied to the study of the runaway process of hydraulic turbines, but the influence of the free surface of upper and lower reservoirs is rarely considered, especially in tubular turbines. In this paper, the external characteristics and internal flow of tubular turbines with reservoirs during runaway process were studied based on the IB-LBM method, which can provide references for the safe and stable operation of tubular turbines.
2. Numerical Methods and Governing Equation

2.1. Numerical Calculation Method
The lattice Boltzmann lattice (LBM) method is a mesoscopic flow method between macroscopic and microscopic flow [7]. The main control equations are as follows:

\[ \frac{\partial f}{\partial t} + \vec{v} \cdot \nabla f = \frac{1}{\tau} [f^{eq} - f] \]  

(1)

Where, \( f \) is the distribution function, \( \vec{v} \) represents the velocity vector of the microscopic particles, m/s; \( \tau \) is the relaxation time, s; \( f^{eq} \) is the equilibrium temporal distribution function.

The IB method based on LBM is that the solid boundary is represented by a set of Lagrangian discrete points with flow around the immersed boundary covered by a series of Euler nodes, on where the density function is defined. Moreover, the interaction force between particles is added to the solid boundary:

\[ f(x,t) = \int g(X,t) \delta(x - X) ds \]  

(2)

The D3Q19 grid model [8] was adopted in this paper for velocity dispersion shown in Figure 1.

![Figure 1. D3Q19 model.](image1)

![Figure 2. 3D model of the turbine.](image2)

2.2. The Equation of Rotational Speed in the Runaway Process
During the runaway process, the rotational speed satisfies the following formula:

\[ M - M_t = J \frac{d\omega}{dt} \]  

(3)

where, \( M \) is the hydraulic moment on the runner, \( M_t \) is the total load of the system, \( J \) is the moment of inertia, and \( \omega \) is the angular velocity of the runner. The increase in the angular velocity at any time \( \frac{d\omega}{dt} \) can be obtained from equation (3) during the runaway process, and then the value of the runner rotation speed can be obtained by adding the value at the corresponding time.

3. Results and Discussion
In this paper, a prototype tubular turbine operating in a hydropower station was modelled, including a runner with 3 blades, 16 guide vanes, a bulb body, and inlet and outlet flow channel, as shown in Figure 2. The nominal diameter of the runner is 7.2 m, the rated flow rate is 412.57 m³/s, the rated power is 22.7 MW, the rated rotational speed is 75 r/min, and the rotational inertia is 560000 kg·m².

The grids around the runner and flow passage of tubular turbine were refined, and the resolution scale of this area was set to 0.16m, while that of reservoirs was 1.28m. As the grid size increase, torque on the runner stabilized and the number of grids was selected 2.53 million.
3.1. Reliability Verification
Table 1 shows three different guide vane opening conditions with a blade opening of 4°. The experiment layout and key devices can refer to reference [9]. Table 2 lists the comparison between the simulated and the experimental value including the torque and power. The errors of the torque and power in three working conditions are all about 5%, which shows that the IB-LBM method can be applied to the study of the tubular turbine.

| Condition | Guide vane opening GVO (°) | Speed n (r/min) | Flow rate Q (m³/s) | Unit speed n₁₁ (r/min) | Unit flow rate Q₁₁ (m³/s) |
|-----------|-----------------|----------------|-------------------|------------------------|------------------------|
| Condition 1 | 60              | 75             | 310.337           | 185.4                  | 2.05                   |
| Condition 2 | 65              | 75             | 299.382           | 218.8                  | 2.34                   |
| Condition 3 | 70              | 75             | 299.624           | 241.0                  | 2.58                   |

3.2. Analysis of Performance during the Runaway Process
The steady-state values of the above three conditions were used as initial values of the runaway process. Figure 3 presents the runaway process curve of the turbine under different guide vane openings when the blade opening is 4°. It can be seen that the law of runaway process at different guide vane openings is roughly similar, starting from the initial condition and ending at the end of the runaway process (M=0). In addition, the larger the guide vane opening, the greater the rotational speed and flow rate change.

The instantaneous parameters of the turbine at any time during the runaway process can be captured based on IBM. The torque, rotational speed, axial force and flow rate are dimensionless through ratio of instantaneous value to the initial value in Eq. (4), where the subscript t, 0 and rel denote instantaneous, initial and relative value respectively.
Figure 4 shows changes of various working parameters over time on condition 1 (blade opening degree 4°, guide vane opening degree 60°). The torque and axial force on the runner gradually decrease to 0 with time increasing. In the initial stage of the runaway process ($t=0-2s$), the torque and axial force drop rapidly, while the flow rate and rotational speed increase. In the middle of the runaway ($t=2-4s$), changes in four parameters slow down. When it reaches the runaway speed, the parameters are basically stable. The runaway speed is 2 times the initial value while the flow rate is 1.2 times.

\[
\begin{align*}
\frac{n}{n_0} &= \frac{Q}{Q_0} = \frac{M}{M_0} = \frac{F}{F_0} \\
\end{align*}
\]

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3.3. Analysis of the Internal Flow Field during the Runaway Transition

During the transition process, the flow pattern inside turbine is complicated. Taking condition 1 as an example, changes of velocity and pressure inside turbine during the runaway process were analyzed.

3.3.1 Velocity Analysis. Figure 5 shows the velocity streamline at different moments of the turbine. When the influence of the free surface of reservoirs are adding, the velocity streamline at the inlet flow channel is turbulent and there are obvious vortices. When the maximum runaway speed is reached, the velocity streamline in the draft tube also become chaos, which may be because of the uneven pressure distribution in the turbine caused by gravity.

![Velocity distribution](image)

Figure 5. Streamline distribution at different moments.

3.3.2 Pressure analysis. Figure 6 depicts the pressure distribution in the turbine at different moments. It can be seen that the pressure on the upstream side of the bulb body gradually increases along the direction of gravity affected by gravity. At the beginning ($t=0$), the pressure distribution in the draft tube is relatively uniform, and a small low-pressure area appears around the shroud of the blades. During the runaway process, the local low-pressure area around the runner begins to diffuse to the draft tube section,
forming a periodic formation, shedding, and diffusion. Cavitation occurs in draft tube due to low-pressure area with uneven pressure distribution in draft tube, causing severe pressure pulsation, which is not conducive to the stable operation of the unit.

![Pressure distribution within the turbine at different time instants](image1)

**Figure 6.** Pressure distribution within the turbine at different time instants

![Pressure distribution on runner blade pressure surface.](image2)

**Figure 7.** Pressure distribution on runner blade pressure surface.

![Pressure distribution on runner blade suction surface.](image3)

**Figure 8.** Pressure distribution on runner blade suction surface.

Figures 7 and 8 respectively show pressure distributions at pressure and suction sides of the runner at different times. At the initial moment of runaway \( t=0 \), the pressure distribution on three blades is not similar. It may be because the influence of the free surface of the upstream reservoir leads to the higher pressure of the blade near the lower side. When the turbine enters the runaway state, the obvious low-pressure area appears on pressure surface around shroud. It may be because the relative flow angle will decrease with the increasing rotational speed, causing the negative attack angle. Then the suction surface will be directly impacted by the flow with occurring a local high-pressure area, leading to the flow separation and vortex on the pressure surface. In addition, negative pressure also occurs on suction sides near hub and the hub, where the overall pressure is lower than the pressure surface.
5. Conclusion
The transient process during runaway in tubular turbine including upstream and downstream reservoirs was investigated based on the IB-LBM method, main conclusions are as follows:
(1) IB-LBM can be well applied to the study of tubular turbine during the runaway process, and the error with the experimental value is only about 5%.
(2) When the unit is runaway, the torque and axial force on the runner drop rapidly, while the flow rate and rotational speed rise rapidly. After reaching the runaway speed, the parameters tend to be stable. The greater the guide vane opening, the higher the rotational speed and flow rate change in runaway.
(3) The pressure of the flow channel gradually increases along the direction of gravity, resulting in a turbulent velocity distribution at the entrance of the flow channel and obvious vortexes. During the runaway process, a large area of negative pressure will appear in the runner with draft tube, and the appearing-shedding-diffusion process presents a certain periodicity. What’s worse, obvious negative pressure area is observed on pressure sides of the blade near the shroud, causing cavitation.

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