Diagnostics of nuclear reactor coolant pump in transition process on performance and vortex dynamics under station blackout accident

Daoxing Ye a, b, *, Xide Lai b, Yimin Luo b, Anlin Liu b

a Key Laboratory of Fluid and Power Machinery, Ministry of Education, School of Energy and Power Engineering, Xihua University, Chengdu 610039, China
b School of Energy and Power Engineering, Xihua University, Chengdu 610039, China

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ABSTRACT

A mathematical model for the flowrate and rotation speed of RCP during idling was established. The numerical calculation method and dimensionless method were used to analyze the flow, head, torque and pressure and speed changes under idle conditions. Regularity, using the Q criterion vortex identification method combined with surface flow spectrum morphology analysis to diagnose the vortex dynamic characteristics on RCP blade. On impeller blade, there is two oscillations in the pressure ratio on pressure surface in blade outlet region. The velocity on the suction surface is two times more oscillating than the inlet of blade, and there is an intersection with the velocity ratio curve on pressure surface. On blade of guide vane, the pressure ratio increases along the inlet to outlet direction, and the speed ratio decreases with the increase of idle time. There is a vortex that rotates counterclockwise on the suction surface, and the streamline on the suction surface of blade is subjected to the entrainment and blocking action of the vortex creates a large reverse flow in the main flow region. There are two vortices at the outlet of guide vane suction side and the vortices are in opposite directions.

1. Introduction

Nuclear energy is an efficient and clean energy source that not only greatly improves the quality of the environment, but also protects the ecological environment on which humans depend [1]. The safe and stable operation of nuclear power plants is one of the global concerns. In the case of power outages in nuclear power plants, it is effective to ensure sufficient time to cool the reactor to comply with safety standards and then numerical methods were used. Calculate and analyze the internal flow rate, rotation speed, and Q criterion of the nuclear reactor coolant pump under idle conditions, and compared the test data of the nuclear main pump of Qinshan and Daya Bay nuclear power plants. In 2008, Liu Xiajie and Wang Dezhong conducted an inertial study of nuclear main pump under idle conditions, and compared the test data of the nuclear main pump of Qinshan and Daya Bay nuclear power plants. In 2011, Xu Yiming used the momentum conservation equation to obtain three models of the idle speed of RCP. The variation law of the speed of the AP1000 and M310 nuclear main pumps was analyzed, and the inertia of the nuclear main pump reached half flow when different moments of inertia were obtained. The variation of the transit time, the model belongs to the semi-theoretical semi-empirical formula, and the friction torque coefficient in the model needs to be obtained through experiments or experience [3]. In 2011, according to the conservation of energy, Hong [4] proposed a mathematical model of the flow and rotation speed of the nuclear main pump under idle conditions, and compared the test data of the nuclear main pump of Qinshan and Daya Bay nuclear power plants. In 2008, Liu Xiajie and Wang Dezong conducted an inertial and vibration displacement test on the main pump of the Lingao nuclear power plant in Guangdong, and fitted it with a four-item multi-speed and flow rate [5]. The measurement results were in compliance with safety standards and then numerical methods were used. Calculate and analyze the internal flow characteristics of RCP [6].

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At present, the identification methods of flow vortex include the Q criterion, J criterion, λ2 criterion, and helicity [7–11]. In 2018, Li Wei used the helicity method to extract the transient flow field vortex core, and analyzed the vortex structure of internal flow of

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inlet section, the impeller and the vane section during the start-up process, and analyzed the start-up process of mixed-flow pump by using the cross-section diagnostic method [12]. In 2016, based on the numerical calculation of Reynolds time-average model and the vortex-discriminating Q criterion, Cao Yu [13] obtained the topological structure of suction surface of blade, capturing the standing foot stationed on blade and the low-pressure bubble freely upstream of impeller, and analyzed its formation mechanism. In 2011, Zhang Xiang [14] used the helicity method to analyze flow characteristics of fluid in stainless steel stamping pump by numerical simulation. In 2010, based on the numerical simulation of internal flow of centrifugal pump during start-up process of centrifugal pump, Li Zhifeng [15] used the distribution of total pressure on flow section and axial component distribution of the boundary vorticity flow to characterize the change of fluid energy and the effect of partial impeller on fluid work.

The above research mainly measured and analyzed the external characteristics of nuclear reactor coolant pump during the inertia process, established a semi-theoretical and semi-empirical formula model, investigated the external characteristics of RCP. In the process of idling, there is a lack of research on the formation and development of internal vortices. Therefore, this paper first established the mathematical model of flow and rotational speed with idle time, and then used the numerical calculation method to verify the accuracy of numerical calculation through the dimensionless analysis of flowrate, head and torque. Finally, the internal of performance and vortex dynamics were studied and analyzed.

2. Experiment test and mathematical model

Typical pressurized-water reactor system is shown in Fig. 1. A pressurized-water reactor uses light water as the reactor coolant and moderator in the state of high temperature and high pressure not boiling in the reactor core using RCP and sends the high-

<table>
<thead>
<tr>
<th>Channel</th>
<th>Parameter</th>
<th>Reference</th>
<th>Electrical Scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Loop 1 flowrate</td>
<td>RCP 025 MD</td>
<td>1.05.0 V</td>
</tr>
<tr>
<td>2</td>
<td>Loop 2 flowrate</td>
<td>RCP 040 MD</td>
<td>1.05.0 V</td>
</tr>
<tr>
<td>3</td>
<td>Loop 3 flowrate</td>
<td>RCP 052 MD</td>
<td>1.05.0 V</td>
</tr>
<tr>
<td>4</td>
<td>Temporary power failure trip signal of RCP</td>
<td>On-off signal</td>
<td></td>
</tr>
</tbody>
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Fig.1. Typical pressurized-water reactor system [16].

Fig.2. Component of nuclear reactor coolant pump.
temperature and high-pressure water to steam generators to generate steam with heat exchangers for a turbine generator to generate electricity.

This test was based on the idle test carried out during the overhaul of a nuclear power plant [6]. The flow signal parameters and motor trip signals of coolant loops required for this test were collected by the KDO data acquisition system, and stored, analyzed, and printed. The flow parameters were shown in Table 1.

Adopt temporary wiring and protection short circuit method, use the corresponding switch to directly stop the three RCP, and use the KDO system (Test data acquisition system of nuclear power station) to record the 025MD, 040MD and 052MD idle flow. The idle characteristics of three pumps were similar. In this study, the first RCP was analyzed.

In the event of a power outage in the nuclear power plant, the nuclear reactor coolant pump started to idle, and flowrate and speed decreased with time. The more details of test data can be caught in Refs. [5,6,17]. In order to accurately describe the law of flowrate and speed change of the RCP during idling, the fifth-order polynomial is used for fitting. The mathematical model of flowrate and speed after fitting is shown in formulas (1) and (2). The Adj.R-square is 0.99659 and 0.9957 respectively. The closer the Adj.R-square is to 1, the better the fit. Which indicating that the flowrate and speed fitting using the fifth-order polynomial is more in line with the experimental test value.

$$Q = 2604.76 - 75.74 \times t + 0.92 \times t^2 - 0.00584 \times t^3 + 2.06 \times 10^{-5} \times t^4 - 3.79 \times 10^{-8} \times t^5 + 2.86 \times 10^{-11}$$  \hspace{1cm} (1)$$

$$n = 58386 - 1762.53 \times t + 21.34 \times t^2 - 0.13 \times t^3 + 3.82 \times 10^{-4} \times t^4 - 4.51 \times 10^{-7} \times t^5$$  \hspace{1cm} (2)$$

where, $Q$ is the percentage of flowrate of design of reactor coolant pump, %; $n$ is speed, r/min; $t$ is time, s.

3. Numerical calculation method

The domain of inlet and outlet section, guide vane and spherical volute was set as stationary system, and the impeller flow field was rotating system [18,19]. The numerical simulation used commercial ANSYS-CFX software platform to calculate the multi-coordinate grid in computational domain [20]. The data exchange between the rotor and stator was performed through interface, and frozen rotor was used between impeller and stationary domain. The time steps of transient were 2s, the initial time of idle rotation was 90s, and the total time of transient calculation was 220s. The inlet boundary was static pressure condition, the static pressure value was set to 15 MPa (RCP inlet pressure); formula (1) was used as the outlet boundary condition of pump, and formula (1) was used as the rotational speed condition of impeller. In the calculation process, all the walls adopted adiabatic and non-slip wall condition.
The near wall area used the scalable wall functions. The wall surface roughness was 0.025 mm. The convergence condition residual was set to $1 \times 10^{-6}$. The RNG $k$-$\varepsilon$ turbulence Model was used. Minimum iteration 60 times was used in a single time step, and maximum iteration was used 80 times.

The component of RCP is shown in Fig. 2. It consisted of impeller, guide vane and volute components. The fluid entered from the inlet of impeller. Under the centrifugal force of rotating impeller, the
The change of flow rate, head ratio and torque ratio with idle time are shown in Fig. 4. The performance characteristics of RCP from the 90s–220s idle process were analyzed. From Fig. 4(a), the flow rate ratio, the fitting formula (1) of the reference flow rate, decreases rapidly with the increase of idle time, and the flow rate drops to 50% after the idle time of 100 s, then slowly decreases to 6.5% at 220s. The head ratio and torque ratio decrease sharply with the increase of the idle time, which is different from the flow ratio change in that the head ratio and torque ratio tend to be horizontal level after 140s, and close to zero. From Fig. 4(b), calculation result of head ratio is in good agreement with the experimental measurement results, and the errors are caused by experimental error and conversion error of experimental prototype.

The variation and distribution of the radial force of RCP impeller are shown in Fig. 5. The variation of radial force with idle time was shown in Fig. 5(a), and the distribution of radial force was shown in Fig. 5(b). The radial force, the magnitude of the “bubble” indicating the magnitude of the radial force, decreases as the idle time increases. As can be seen from Fig. 5(a), after the RCP is powered off, the radial force rapidly decreases with the increase of idle time. After 140 s, it tends to be horizontal level, and the variation is similar to the head and torque. The radial force gradually decreases during the idle transition of RCP impeller shown in Fig. 5(b), and the flowrate decreases after idling, so the differential pressure changes gradually to zero.

4. Data processing method

For convenience of analysis, the dimensional flowrate, head, torque and pressure and velocity in the internal flow field under the inertia condition of RCP were defined.

\[ Q_f = \frac{Q_t}{Q_d}, \quad H_f = \frac{H_t}{H_d}, \quad T_f = \frac{T_t}{T_d} \]  \hspace{1cm} (3)

\[ P_f = P_t / (\tfrac{1}{2} \rho U^2), \quad V_f = V_t / U \]  \hspace{1cm} (4)

where \( Q, H, T, P, \) and \( V \) were the dimensional flow rate, head ratio, torque ratio, and pressure ratio and velocity ratio, respectively; \( Q_d, H_d, T_d, P_d \) and \( V_d \) were the RCP transients during idle process, respectively. The unit of flowrate, head, torque and pressure and speed were \( \text{m}^3/\text{h}, \text{m}, \text{N-m}, \text{Pa}, \text{m/s}; Q_d, H_d, T_d, \) and \( U \) were RCP in design conditions. The unit of flowrate, head, torque and fluid density and circumferential velocity of the outlet diameter of impeller were \( \text{m}^3/\text{h}, \text{m}, \text{N-m}, \text{kg/m}^3, \text{m/s}. \)

5. Results and analysis

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5.1. Performance analysis of blade

The schematic of flow direction in impeller and guide vane of RCP is shown in Fig. 6. The impeller rotates around the central shaft, wherein the distance from point on the blade to rear cover is the chord length of blade, and the maximum chord length is between front cover and rear cover, and the distance is 1. The distance between leading edge and trailing edge of blade is defined as spanwise. The fluid flows in from the inlet of impeller, and then energy was increased in guide vane, flowing out of the outlet of impeller.

5.1.1. Load analysis of the blade system

The relationship between pressure ratio and velocity ratio distribution on impeller blades at different idle times when the chord length of impeller is 0.5 is shown in Fig. 7. It can be seen that the pressure difference between the outlet and inlet of blade increases as the idle time increases as a whole. At 200s, it can be found that the pressure difference between the inlet and outlet of the blade
Fig. 7. Pressure ratio and velocity ratio distribution on impeller blade when span was 0.5 ((a): pressure ratio, (b): velocity ratio).
Fig. 8. Pressure ratio and velocity ratio distribution on guide vane blade when span was 0.5 ((a): pressure ratio, (b): velocity ratio).
and the pressure surface and suction surface is small. It shows that the blade load is reduced and the impeller bears less torque. The velocity ratio gradually decreases with the increase of idle time. The pressure ratio on pressure surface as a whole is higher than the pressure ratio on suction surface. In the blade outlet area, as indicated by the dotted line in Fig. 7, there is two oscillations in the pressure ratio on blade pressure surface, as shown in Fig. 7(a). It can be seen from Fig. 7(b) that the velocity on the suction surface is two times oscillating (two peaks) near the inlet of the blade from the leading edge to trailing edge of blade, and then gradually decreasing, and there is an intersection point of velocity ratio curve on the suction surface. At the same time, the velocity is also oscillating near the trailing edge of the blade.

Fig. 8 shows changes in pressure ratio and velocity ratio distribution on the blade at different idle times when the chord length of the guide vane blade is 0.5. After the RCP is de-energized, the distribution of pressure ratio from the leading edge to trailing edge of blade gradually changes from a rising trend to a horizontal trend with an increase in the idle time from Fig. 8(a). At 200s, The pressure ratio of the leading edge to trailing edge of the blade is almost equal, and the pressure ratio between pressure surface and suction surface of blade is also at the same level, indicating that pressure inside RCP is in the direction of leading edge to trailing edge of blade as the idle time increases, and the gradient is lowered. As the idle time increases, the distribution of the speed ratio from the leading edge to trailing edge of blade gradually changes from a decreasing trend to a horizontal tendency shown in Fig. 8(b). The velocity of pressure surface and suction surface of guide vane blade tends to equal.

5.1.2. Pressure ratio and velocity ratio distribution of impeller and vane

The distribution of pressure ratio and the velocity ratio with the increase of idle time in flow direction from inlet to outlet of RCP impeller is shown in Fig. 9. Since there is a distance between the inlet of impeller and the leading edge of impeller blade, the pressure ratio changes little before 0.4, and the pressure ratio of fluid increases under the motion of rotating blade. At the same time, the pressure ratio increases as idle time increases. The velocity ratio is gradually reduced, but pressure ratio at the outlet of impeller is substantially equal, as shown in Fig. 9(a). The velocity ratio decreases as the idle time increases. The velocity ratio changes less
before 0.6, then which begins to decrease and reaches a minimum near 0.8, and finally it increases gradually, reaching a maximum at outlet of impeller.

The curves of pressure ratio and velocity ratio along the inlet to outlet of guide vane blade at different idle times shows in Fig. 10. The pressure ratio gradually decreases with the increase of idle time from Fig. 10(a). The pressure ratio increases first in the range of 1.0–1.2, and then decreases in the range of 1.2–1.4 on the inlet to outlet of blade of guide vane blade, and the final value rises, but as the idle time increases overall increase tends to decrease. The velocity ratio decreases as the idle time increases as shown in Fig. 10(b).

5.2. Dynamics analysis of vortex structure

From the second-order tensor characteristics, the characteristic equation of the local velocity gradient tensor of the incompressible flow can be written as,

$$\lambda^3 + Q\lambda - R = 0$$

If $\lambda_1, \lambda_2$ and $\lambda_3$ are three roots, then there are three independent invariants between them, so
\[ Q = -\frac{1}{2} (e_{ij} \epsilon_{ji} + \Omega_{ij} \Omega_{ji}) = \frac{1}{2} (||\Omega||^2 - ||E||^2) \]  

(6)

where, \( \epsilon_{ij} \), \( \Omega_{ij} \) are strain rate tensor and vorticity tensor respectively, and \( \Omega_{ij} = -\Omega_{ji} \), \( ||E||^2 = e_{ij} \epsilon_{ji} \) and \( \Omega_{ij} = -\Omega_{ji} \), \( ||\Omega||^2 = 0.5|\omega|^2 \).

In this paper, the \( Q \) criterion proposed by Hunt et al., in 1988 was used to identify the vortex region in flow field of RCP, so as to identify the vortex structure in impeller and guide vane to achieve the purpose of visualization. \( Q \) criterion was defined as \( ||E|| \) and \( ||\Omega|| \) represent the deformation and rotation of a point in the flow field, respectively, and the area of \( Q > 0 \) was defined as a vortex, which means \( ||\Omega||^2 - ||E||^2 > 0 \). In this rotating field, the magnitude of the vorticity, in the region of the vortex played a dominant role in angular strain rate, and the vortex flow field of different sizes in the flow field could be identified by different values of \( Q \). In the rotating flow field of different sizes in the flow field could be identified by different values of \( Q \).
core nuclear coolant pump, for ease of analysis the velocity of fluid in impeller flow channel was relative velocity, and the fluid in guide vane used the absolute speed.

The streamline and vortex distribution on the pressure surface of impeller blade are shown in Fig. 11. The streamline is significantly curved near the leading edge of blade and the front cover area, where the vortex is formed as shown in Fig. 11. The outer vortex intensity decreases with the idle time increases. The streamline distribution of blade pressure surface dose not change significantly with the increase of idle time, and the streamline is concentrated near the leading blade and the rear cover.

The streamline and vortex distribution on pressure surface of impeller blade are shown in Fig. 12. There is a vortex that rotates counterclockwise near the blade root where is at inlet side and rear cover, and the streamline on the suction surface of blade is sucked and blocked by vortex. The entrainment and blocking action create a large reverse flow in flow field. Before the idle time 200s, the vortex is mainly distributed in the vicinity of front cover region.

The streamline and vortex on pressure surface of guide vane blade is shown in Fig. 13. The surface streamline and vortex are analyzed. Before the idling, t = 90s and t = 130s, there are two obvious vortices on pressure surface of guide vane blade. One of which is located in the leading edge of blade and near the front cover as shown in Fig. 13(a), 13(b), and 13(e). The other larger vortex is located in the middle flow area and effecting all the flow field. The streamline from leading edge of blade comes in, which deflects under the action of vortex and is squeezed into the main flow field, and there is reflow near the front cover. The flow in Fig. 13(c), and 13(d) is relatively stable.

Fig. 14 shows the streamline and vortex distribution on suction surface of guide vane blades at different inertia moments of RCP. There are two vortices at the trailing edge of guide vane blade. From the streamline distribution on suction surface, it can be clearly judged that the two vortexes are in opposite rotating direction. A vortex is created on the inlet side of blade which was shown in the red area of blade on $Q_c$ chart in Fig. 14. Streamlines are crowded into the middle flow area by the action of two vortices so that the dissipation loss of flow is increased.

As idle time increases, the vortex structure evolution in impeller flow path are shown in Fig. 15. The vortex area is distributed on the inlet and outlet of blade and the pressure surface of trailing edge of blade, and the vortex on trailing edge of blade pressure surface gradually disappears as the idle time increases. At $t = 130s$ the flowrate is 26%, the vortices on the trailing edge of blade pressure surface almost disappeared shown in Fig. 15(e). At the idle time $t = 200s$, the vortices on pressure surface of blade in not existed. Before idling, RCP is operating under design flowrate condition, so the flow in impeller is stable, and the fluid in flow field is dominated by strain rate. As the idle time increasing the flow rate decreases and the impeller speed decreases, and the flow characteristic is also strain rate flow in field, but the $Q_c$ value increases.

The vortex structure of guide vane evolution at different idle time is shown in Fig. 16. The fluid flows out of impeller after being subjected to work by centrifugal force and forms a strong vortex in the stationary guide vane flow channel, and vortex is distributed periodically along the circumferential direction. As the idle time increases, the vortex area of fluid in guide vane decreases. When the idle time is 200s and the flowrate is 9%, the distribution of $Q_c$ value in Fig. 16(f) that the cloud map in range of $-333.33s^{-2}$-$333.33s^{-2}$ increases, and the vorticity decreases, indicating that the vorticity is equivalent to strain rate of fluid in guide vane.

### 6. Conclusions and discussions

In order to study the transient performance of reactor coolant pump during power failure and to analyze the vortex dynamic
characteristics in impeller and guide vane flow channel, a mathematical model of flow rate and speed of reactor coolant pump during idling was first established, and then the numerical calculation method was used to calculate the characteristics of RCP, and the dimensionless method was used to analyze the flow, head, torque, pressure and speed changes under the idle condition. Finally, the Q criterion vortex identification method was used. The vorticity distribution on blade was analyzed by combining the surface flow morphology. The conclusions are as follows.

(1). The flow ratio decreases rapidly with the increase of idle time. The flow rate drops to 50% after 100 s of idle time and decreases to 6.5% at 220 s. On the impeller blades, there are two oscillations in the pressure ratio on pressure surface in blade outlet region. The velocity on the suction surface is two times more oscillating than the inlet of blade, and there is an intersection with the velocity ratio curve on pressure surface. At the same time, the velocity is also oscillated near the outlet of blade. In the flow direction from the inlet to the outlet of impeller, the pressure ratio gradually increases. As the idle time increases the rate of increase of the pressure ratio decreases gradually, and the speed ratio decreases first and then increases, reaching a maximum at the impeller outlet.

(2). On the blade of guide vane, the pressure ratio increases along the inlet to outlet direction, and the speed ratio decreases with the increase of idle time, and the distribution trend gradually changes from decrease to the level. In the upward flow from the inlet to outlet of blade, the pressure ratio gradually decreases with the increase of idle time, and the pressure ratio first increases first, then decreases, and finally rises, but as the idle time increases, the overall increase trend weakened.

(3). The streamline is significantly curved near the impeller blade inlet and the front cover region, and the vorticity is weakened as the idle time increases. There is a vortex that rotates counterclockwise on the suction surface, and the streamline on the suction surface of blade is subjected to the entrainment and blocking action of the vortex creates a large reverse flow in the main flow region. On the vane blade, a large vortex interferes with the all flow field. The streamline is deflected from the inlet of guide vane blade and is squeezed into the main flow field, with recirculation near the front cover. There are two vortices at the outlet of guide vane suction side and the vortices are in opposite directions. The vortex area in the flow channel is mainly distributed on the inlet and outlet of impeller blades and the trailing edge of pressure surface, and the vortex on the trailing edge of blade.

Fig. 16. Vortex structure in guide vane passage (Q-criterion).
pressure surface gradually disappears with the increase of idle time. A strong vortex is formed in the guide vane channel. And periodically distributed along the circumferential direction of the vane, and as the idle time increases, the swirl region of fluid in guide vane decreases.

Declaration of competing interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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