Numerical Analysis of reactor coolant pump performance under reverse conditions

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Abstract: Since no anti-reverse device is equipped in the system of the third generation AP1000 of nuclear power plant, the reactor coolant pump (RCP) might operate in the reverse condition. However, it is hard to carry out the experiments of RCP in reverse condition due to its high temperature and special thrust bearing (their thrust bearing may not afford the reverse condition either). Hence, CFX with unsteady RANS turbulence model is employed to thoroughly study the characteristics of the reactor coolant pump in reverse pump mode as well as the normal pump condition. Their different flow patterns between the normal case and the reverse case are compared. It is found that a beat frequency captured in the impeller in the reverse case is suggested to be the diagnostic signal of the generation of reverse condition.

KEYWORDS: Reactor coolant pump, reverse condition, instability, pressure fluctuation

1. Introduction

The third generation of nuclear power plant AP1000 is under operation in China recently. The reactor coolant pumps (RCP), as the unique rotating equipments in this system, play key roles for the safety of the AP1000. To be noticed, there is a big difference between the former generations and the third generation AP1000 due to the anti-reverse device (with this device, pump reverse condition is avoided). In the second generation, the reactor coolant pump is with anti-reverse device, while in the third generation AP1000, there is no anti-reverse device near the pumps, as shown in figure 1. Hence, the pump reverse condition might occur in some special cases. Meanwhile, the RCP can’t afford the reverse condition due to its special thrust bearing. In a word, the reverse condition might be dangerous to the system as well as the thrust bearing of RCP in AP1000. Hence, the performance of the reverse phenomenon in the third generation is quite significant. This paper applied the unsteady 3-D computational method to RCP in reverse condition.
Many researchers studied the special flow pattern of RCP in AP1000, yet pump reverse mode is not noticed until now. Zhu et al. researched the complete characteristics [1]. Long et al. studied the instability with uniform inlet flow of AP1000 experimentally [2]. Want et. Al researched the same flow pattern numerically [3]. Still, no researchers studied clearly the whole performance of reactor coolant pump in reverse mode.

In other fields, many researchers studied pump reverse mode. However, their results can’t apply to the RCP directly due to different pump geometry structure as well as the complex flow pattern inside the reverse pump condition. Zhang et al. study the vortex in the impeller passage in the reverse pump mode of some pump turbine with new omega vortex identification [4]. Li et al. research the reverse pump mode in some pump turbine with the detached eddy simulation(DES), and found that a low signal of pressure fluctuation appeared in the this model, due to the vortex inside the draft tube[5]. Li et al. numerically studied the shut-down progress in some pump turbine including the turbine braking mode and reversed pump mode, the negative torque on the runner as well as the decreasing flow rate are captured during the guide vanes closing [6]. Zhu & al. research the effect of pumping chamber outlet contraction angle with fluent in some reactor coolant pump, and points out that the backflow is the main influencing factor between the chamber and outlet [7]. Kant et al. numerically researched the S-shaped blades and pointed out that a difference of 15% pump head are captured between normal condition and reverse condition, and their pressure fluctuation characteristics are similar between both conditions [8]. Wang et al. numerically researched the S zone in pump turbine, including reverse pump, small torque and so on. And they found that the amplitude of pressure fluctuation firstly increased and then decreased with the discharge decreasing [9]. Wang et al. investigate the pressure fluctuation inside the centrifugal pump at low flow rate with detached eddy simulation (DES), and they point out that the dominated frequencies in the impeller are the frequency of rotating speed and its integer multiples[10].

In a word, most of the researchers find the high amplitude pressure fluctuation, asymmetric flow pattern inside impeller passage as well as the negative runner torque, due to the reverse pump mode. However, different types of impeller are with different characteristics of reverse pump modes. Such as the pumps with the low specific speed, the higher pump heads in reverse pump mode, while the higher specific speed, the lower pump head in reverse pump mode. Hence, the characteristics of RCP in AP1000 need to be further studied specifically. Hence, the methodology of numerical simulation is better to research the reverse condition of RCP.

This paper studies the flow pattern of reverse pump condition of RCP in AP1000, and it employs K-omega turbulence model as the numerical simulation model, due to its advantage feature in separated flow. The results of numerical simulation found that a beat frequency in reverse pump mode exists, and it might cause strong solid vibration and noise. This beat frequency, as an evidence of diagnosis, is induced to be recognized as the generation of the reverse pump mode.

2. Calculation model
The calculation model is a reduced model based on the RCP of AP1000. Its flow geometry is shown in Fig. 2. In the normal condition, the coolant flow directly enters from the outlet of the lower sealing head of the steam generator, to the impeller, the guide vane, the volute, and finally flows to the reactor pressure vessel. Its impeller diameter is 90mm, and other relevant parameters are calculated according to the similarity law of the pump.
3. Grid independence verification
Meshing is a very critical step in current CFD technology. The density of the grid not only affects the accuracy of the results, but also reflects the economic utilization of computing resources. The grid-independence check is to find a balance between accuracy and economy and find the suitable number of grids. The model in this paper uses ICEM to build an unstructured grid. Grid-independent verification was performed at the best efficiency flow rate of the pump at 1480 rpm. The inlet applies a static pressure inlet and the outlet is mass flow outlet. 6 sets of grids are employed, as shown in table 1.

| Grid   | straight pipe | Impeller  | Guide vane | Volute  | total       |
|--------|---------------|-----------|------------|---------|-------------|
| Grid 1 | 935 572       | 2 620 992 | 7 199 651  | 7 079 233 | 17 835 448 |
| Grid 2 | 543 745       | 1 729 926 | 3 835 119  | 4 127 990 | 10 236 780 |
| Grid 3 | 343 702       | 1 230 950 | 2 712 688  | 2 150 179 | 6 437 519  |
| Grid 4 | 230 592       | 929 269   | 1 995 737  | 1 778 618 | 4 934 216  |
| Grid 5 | 161 946       | 669 291   | 1 516 008  | 1 264 129 | 3 611 374  |
| Grid 6 | 120 521       | 539 569   | 1 185 643  | 1 071 881 | 2 917 614  |

Fig. 3 shows the results of the mesh check. As the number of mesh increases, the curves of head and efficiency change from higher to lower, and is gradually stabilizes. The efficiency curve is basically stable. This paper selects grid 4 for the consequence calculation and analysis.
4. Analysis of hydraulic performance results

4.1. General characteristics analysis
This section generally compares the characteristics between normal case Z and the reverse case A. Though they get similar value of pump head, their frequency and pressure are different. As shown in table 2.

Table 2: Pump parameters of case A and case Z

| case          | Mass Flow \(Q_m\) (kg/s) | Rotating speed \(\eta\) (rpm) | Head \(H_m\) (m) | Frequency conversion \(f_n\) (Hz) | Pressure pulse (Hz) |
|---------------|------------------------|-------------------------------|-----------------|----------------------------------|---------------------|
| A (reverse case) | -4.4753                | -1253.2                       | 0.5468          | -20.9                            | -83.5               |
| Z(normal caseZ) | 8.81                   | 1480                          | 0.5516          | 24.7                             | 98.7                |

4.2 Flow characteristics in the impeller
As shown in Fig. 4, the impeller is equipped with 11 monitoring points, located at the semi-high surface of the blade individually. Y11, Y12 and Y13 are located on the intersection line between the midline section of the two blades and the semi-high surface of the blade, and are evenly distributed from the axial direction. Y21, Y22, Y23 are close to the suction surface of the blades, and Y31, Y32, Y33 are near the pressure surface of the blades. The relative positions of Y12L and Y12R and the blades are similar distributed as Y12 in adjacent flow paths.
Fig. 5 shows the time domain distribution of pressure fluctuation of Y11, Y21, and Y31 at case A (reverse condition). Fig. 6 shows the time domain distribution of pressure fluctuation at Y11, Y21, and Y31 at case Z (normal condition). There are big differences between case A and case Z. The waveform of positions Y11, Y21 and Y31 in case A are beat waves, while the pressure of the three monitoring points at case Z is with no shape of the beat wave, and they change significantly with the varieties of the positions at case Z. To be noticed, the beat frequency causes the vibration and noise of the equipment, and it can be used as an identification method for abnormal working conditions.
Figure 6. Time-domain distribution of pressure pulsations at point Y11, Y12, Y13 in case Z (normal condition)

Fig. 7 shows the pressure frequency distribution of three monitoring points Y11, Y12, Y13 at case A. It can be observed that the main frequency is 11 times of runner revolution, caused by the influence of the guide vanes. There is also the second harmonic at 22 times of runner revolution and the weaker third and fourth harmonics. Furthermore, the low frequency part is occupied by the rotating frequency of the impeller. Its second and third harmonics also exist and their amplitudes are less than the second harmonic above. In a word, it can be seen that the pressure fluctuation is more affected by the guide vanes than the impeller. Besides, it can be seen the amplitude of the Y13 point (close to the guide vanes) is the largest, and the amplitude of the Y11 point (far from the guide vanes) is the smallest. However, their amplitude of the revolution frequency keeps stable with the variation of the positions.

Figure 7. Impeller pressure pulsation frequency domain distribution in central flow space of condition A

Fig. 8 shows the frequency distribution of the pressure fluctuation at three monitoring points Y11, Y12, Y13 in case Z. It can be seen that the pressure fluctuation is also affected by the guide vane, for its main frequency is 11 times of runner revolution. However, the amplitude is high and narrow, which is difference with that in the reverse case A. Furthermore, they are also greatly affected by the impeller rotating as shown in figure8. The amplitude of the pressure fluctuation at the monitoring point Y13 (close to the impeller) is the highest, which is different with the pressure fluctuations in case A. It is caused by the different flow pattern in the impeller between case Z and case A.
Figure 8. Pressure frequency distribution of the central flow space in case Z.

Fig. 9 is the surface flow on the pressure surface and suction surface of the impeller in case A. The eddy of the fluid on the pressure surface is strong, due to the reverser condition. The pressure surface actually plays the role of the "suction side" in reverse case. However, it does not flow smoothly caused by its convex shape, and it finally promotes the formation of the vortex belt near the pressure surface.

![Streamline for Case A](image)

Figure 9. Impeller pressure side and suction side of the streamline

5. Conclusions
This paper researches the unstable flow phenomena under pump reverse mode. The reverse flow pattern of the RCP in case A is different with that in general case E. The internal flow of the reverse impeller is complicated. Firstly it is easy to generate beat frequency, causing strong solid vibration and noise, while there is no such phenomenon in the normal case. This beat frequency above can be used as an identification method for abnormal conditions. Secondly, The fluid flows into the impeller with the flow direction changed, generating a vortex band in the impeller flow passage in reversal case A.

NOMENCLATURE
| Symbol | Description                                           |
|--------|-------------------------------------------------------|
| QmP    | Flow rate of the prototype pump (m^3/s)              |
| QmM    | Flow rate of the model pump (m^3/s)                  |
| λ      | Reduction ratio of the model pump                    |
| HM     | Head of the model coolant pump (m)                   |
| n      | Main coolant pump speed (rpm)                        |
| φ      | the energy increment                                 |
| Pout   | Outlet pressure of pump (Pa)                         |
| Pin    | Inlet pressure of pump (Pa)                          |
| ρ      | Density of water (kg/m^3)                            |
| g      | Gravity (m/s^2)                                      |

6. Reference

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