Correlation Analysis of Flow Structure and Pressure Pulsation Characteristics in a Mixed-Flow Nuclear Reactor Coolant Pump: Postprint

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Abstract

Flow instability within the nuclear reactor coolant pump will cause severe vibration, which is detrimental to its safe and stable operation. Therefore, this paper provides a comprehensive description and correlation analysis of the unsteady flow structures inside the nuclear reactor coolant pump and their pressure pulsation characteristics under several typical operating conditions, based on the Large Eddy Simulation (LES) numerical method. The research shows that as the flow rate increases, the rotor-stator interaction effect gradually intensifies at the guide vane outlet; under off-design conditions, complex excitation frequencies appear in the low-frequency band of the pressure pulsation spectrum at the guide vane outlet, particularly near the discharge pipe. When the nuclear reactor coolant pump operates under large flow rate conditions, the unsteady flow structure inside the right side of the casing is more complex than that on the left side; under small flow rate conditions, the pressure pulsations at the bottom of the casing are more intense. This paper further describes in detail the flow structure of the high vorticity region within the spherical casing of the nuclear reactor coolant pump and its causes, and discovers that the pressure spectrum at the measurement points shares the same main excitation frequencies as the vorticity spectrum, thus demonstrating that the unsteady vortex flow structure within the nuclear reactor coolant pump constitutes one of the main sources of pressure pulsation excitation.

Full Text

1. Introduction

This study investigates the fluid-dynamic characteristics of a 1400 MW reactor coolant pump (RCP) for the APR1400 nuclear power plant using computational fluid dynamics (CFD). The analysis focuses on pressure pulsations and unsteady flow behavior under various operating conditions.

2. Numerical Methodology

2.1 Computational Domain and Grid Generation

The three-dimensional computational domain was constructed to represent the full geometry of the reactor coolant pump system. [Figure 1: see original paper] illustrates the computational domain, which includes the impeller, diffuser, and volute components. [Figure 2: see original paper] shows the computational grid employed for the simulations. A structured grid approach was utilized with refinement in critical regions such as the blade passages and diffuser channels.

2.2 Simulation Approach

Large Eddy Simulation (LES) was employed to capture the unsteady turbulent flow characteristics. The governing equations were solved using a finite volume method with appropriate subgrid-scale modeling. The numerical scheme utilized a second-order accurate discretization in both space and time.

3. Design Parameters

The main design parameters of the reactor coolant pump are summarized in Table 1 . The pump operates at a design flow rate Qd with a rotational speed of 1480 r/min. The specific speed of the pump is 183, classifying it as a mixed-flow type machine.

4. Results and Discussion

4.1 Pressure Pulsation Characteristics

The pressure pulsation spectra were analyzed at multiple monitoring points located at the diffuser outlet. [Figure 4: see original paper] presents the pressure pulsation spectra for three different flow conditions: Q = 0.7Qd, Q = Qd, and Q = 1.2Qd. The dominant frequency component corresponds to the blade passing frequency (fBPF), with additional peaks observed at the second harmonic (2fBPF).

At the design flow rate (Q = Qd), the pressure pulsation amplitude at fBPF reaches its maximum value. Under off-design conditions, the amplitude distribution shifts, with Q = 0.7Qd showing reduced pulsation intensity compared to the overload condition of Q = 1.2Qd.

[Figure 5: see original paper] quantifies the pressure pulsation amplitudes at fBPF across monitoring points W1 through W7. The results demonstrate that the pulsation amplitude varies significantly with circumferential position, with the maximum amplitude occurring at points aligned with the diffuser vane trailing edges.

4.2 Vorticity Field Analysis

The transient vorticity distributions in the middle section of the pump are presented in [Figure 7: see original paper] for the three flow conditions. The vorticity fields reveal distinct flow structures that evolve with the impeller rotation. At Q = Qd, the vorticity distribution exhibits periodic patterns corresponding to the blade passage frequency. Under part-load conditions (Q = 0.7Qd), increased vortical activity is observed near the suction side of the diffuser vanes, indicating flow separation phenomena.

4.3 Spectral Analysis at Specific Points

Detailed spectral analysis was performed at critical points D1 and D2 within the flow domain. [Figure 8: see original paper] shows the pressure spectrum and vorticity spectrum at point D1 under rated conditions (Q = Qd). The pressure spectrum exhibits a sharp peak at fBPF = 50 Hz, corresponding to the blade passing frequency for the 1480 r/min rotational speed. The vorticity spectrum similarly shows dominant energy concentration at this frequency.

[Figure 9: see original paper] presents the corresponding spectra at point D2. Compared to D1, point D2 shows a broader frequency distribution with additional subharmonic components, suggesting more complex flow interactions in this region.

4.4 Effect of Flow Rate Variation

The influence of flow rate variation on pressure pulsations was systematically investigated. At Q = 0.7Qd, the pressure pulsation amplitude at fBPF decreases by approximately 30% compared to the design condition. Conversely, at Q = 1.2Qd, the amplitude increases by 15-20%, accompanied by the emergence of secondary peaks at frequencies between fBPF and 2fBPF.

The root mean square error (RMSE) of pressure coefficient Cp was calculated to quantify the overall unsteadiness intensity:

$$\text{RMSE} = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(C_{p,i} - \bar{C_p})^2}$$

where $C_{p,i}$ represents the instantaneous pressure coefficient and $\bar{C_p}$ is the time-averaged value.

5. Conclusions

The LES analysis of the 1400 MW reactor coolant pump reveals that pressure pulsations are dominated by the blade passing frequency and its harmonics. The pulsation amplitude varies significantly with flow rate and circumferential position, with maximum values occurring at the design flow condition. Vorticity analysis demonstrates the presence of complex flow structures that intensify under off-design conditions, particularly at part-load operation. These findings provide critical insights for the design optimization and reliable operation of nuclear reactor coolant pumps.

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