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# Numerical study on the effect of the diffuser blade trailing edge profile on flow instability in a nuclear reactor coolant pump

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## HIGHLIGHTS

- The influence of the different diffuser BTE profiles on the flow instability in RCP is explored.
- The pressure pulsations are extremely asymmetrical in the circumferential direction.
- Two high axial-vorticity magnitude regions are captured on the mid-span.
- The appropriate diffuser BTE profile would also diminish Von Kármán vortices.

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## ABSTRACT

The shedding flow structures from the diffuser blade trailing edge, usually known as Von Kármán vortices, are complicated and crucial to the safe operation of the nuclear reactor coolant pump (RCP), if the shedding frequency reaches the resonant frequency of the diffuser. In the present study, numerical investigation is conducted to analyze the effect of the diffuser blade trailing edge (BTE) profile on the flow instability in a nuclear reactor coolant pump. Five typical diffuser BTEs are analyzed including original trailing edge (OTE), circular trailing edge (CTE), suction surface trailing edge radius 45 mm (STER 45), suction surface trailing edge radius 60 mm (STER 60) and suction surface trailing edge radius 75 mm (STER 75). Results show that by changing the diffuser BTE profile, the vortex shedding intensity from the trailing edge would be diminished, and unsteady flow structures in the spherical casing are more uniform with the well modified diffuser BTE profile. When adopting the cases of STER 45, STER 60 and STER 75, pressure pulsations decrease at the diffuser outlet, but increase at the right side of spherical casing wall. From axial-vorticity distribution, it is indicated that the appropriate BTE profile can effectively prevent flow separation and change evolution of separate flow especially near the discharge nozzle. Besides, it would also diminish Von Kármán vortices from the diffuser BTE, and improve the RCP hydraulic efficiency.

## 1. Introduction

The nuclear reactor coolant pump (RCP) is a significant rotating facility of the reactor core cooling system in the nuclear power plants (NPPs) (Cho et al., 2014; De et al., 2014). The RCP casing as the main pressure boundary of the primary circuit is important for the pump safety. Thus, the casing of the RCP is designed by spherical shape to increase its pressure bearing capacity (Knierim et al., 2005; Baumgarten et al., 2010). However, such a design would cause the RCP efficiency reduced. In order to achieve the goal of high strength, the efficiency of the RCP is really quite low. Thus, from the perspective of flow instability, the complex internal unsteady flow structures induced flow loss and the pressure pulsation will be detrimental to the safety of the operation in the RCP (Gao et al., 2011;Alatrash et al., 2015). In addition, the diffusers in the RCP are used not only to provide appropriate direction to the flow discharged from impeller but also to enhance the pressure recovery (Ling et al., 2015), and the diffusers may also become useful to guide the flow to such a huge spherical casing. But with the continuous operation of RCP, the vortex shedding from the diffuser blade trailing edge (BTE) may cause the fatigue failure and vibration. If vortex shedding frequency is equal to the natural frequency of some unit, it will cause the resonance of the unit (Dörfler et al., 2013; Heskestad and Olberts, 1960). For RCP, these fluctuating flows and unsteady vortexes shedding would significantly affect the performance and stability for the pump system.

As for vortexes shedding from the BTE, many studies demonstrate that it is closely associated with the BTE profile (Heskestad

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**Nomenclature**

| | |
|---|---|
| $Q_N$ | nominal flow rate |
| $H_N$ | design head |
| $\Phi_N$ | nominal flow coefficient |
| $\Psi_N$ | nominal head coefficient |
| $n_d$ | nominal rotating speed |
| $C_p$ | pressure coefficient |
| $\eta$ | pump hydraulic Efficiency |
| $\zeta_d$ | loss of diffuser |
| $\zeta_c$ | loss of casing |
| *RMSE* | root Mean Square Error |
| $f_{BPF}$ | blade passing frequency |
| $\overline{C_p}$ | pressure mean load |

and Olberts, 1960; Do et al., 2010; Neto and Saltara, 2009; Gajić et al., 2010; Zobeiri et al., 2012). And the BTE profile plays a major role on the wake dynamic and resulting structural vibration (Zobeiri et al., 2009; Wu et al., 2015; Yao et al., 2014). In the 1960s, Heskestad (Heskestad and Olberts, 1960) and Toebes (Toebes and Eagleson, 1961) are the early researchers concerning the influence of the BTE profile on hydraulic-turbine-blade vibration. Heskestad (Heskestad and Olberts, 1960) studied the effects of the BTE profile on the vortex induced vibration of a blade, and the amplitude of the induced vibrations increased with the increasing strength of a vortex in the von Kármán vortex street of the wake. Toebes (Toebes and Eagleson, 1961) explored the effects of the BTE profile and elastic properties of plate support and gave the confirmation of the formulated equation of motion. Recently, Do et al. (2010) also investigated two-dimensional turbulent flows over hydrofoils with different blunt BTE configuration using unsteady Reynolds-averaged Navier-Stokes (URANS) equations. They found that the intensity of the vortex strengths at the BTE is amplified when the degree of bluntness is increased, which leads to an increase in the mean square pressure fluctuations. Neto and Saltara (2009) investigated the 2D flow around 13 similar stay-vane profiles with different BTE profiles to determinate the main characteristics of the excitation forces. They considered that not only the BTE thickness itself affected the exciting frequency of stay-vanes, but also the way that the geometry changes were relevant due to changes in the separation region. Zobeiri et al. (2012, 2009) studied the effect of the oblique BTE influencing vortex induced vibration at high Reynolds number. They believed that the collision between upper and lower vortices and the resulting vorticity redistribution were the main reason of the vibration reduction obtained with the oblique BTE.

Different BTE profiles are also used in the pump, and several researchers explored the effect of the BTE profile on the performance and flow instability. Wu et al. (2015) applied BTE modification method based on BTE rounding in the suction surface to widen the operating range of a mixed-flow pump. They found that BTE modification can effectively improve the performance of the mixed-flow pump with large flow rate. Gao et al. (2016) analyzed the effect of the impeller BTE profile influencing the performance and unsteady pressure pulsations in a low specific speed centrifugal pump. The vorticity distributions at different impeller BTE showed that the well-designed BTE profile could reduce vortex intensity, which leads to attenuated rotor-stator interaction.

The objective of this paper is to explore the influence of the different diffuser BTE profile on the flow instability in the RCP. This study considers five typical diffuser BTE, which are based on the method of modification BTE made by Heskestad and Olberts (1960). Numerical methods are applied to achieve different pump performances and unsteady flow characteristics by mounting several monitoring points on the diffuser blade outlet and spherical casing. Finally, effects of different BTE profiles of the RCP on the flow instability are carried out and discussed.

## 2. Model pump

### 2.1. Main parameters

A RCP mixed-flow model pump with a spherical casing and a mixed-flow impeller and a radial diffuser was first designed for investigation, which is employed for the next generation power station unit named as CAP1400 used for China. The main design parameters of the RCP are shown in Table 1. Meanwhile, the com-

**Table 1**
Main design parameters of the RCP model pump.

| Parameters | Value |
|---|---|
| Nominal flow rate $Q_N$ | 0.236 $m^3/s$ |
| Design head $H_N$ | 12.7 m |
| Nominal flow coefficient $\Phi_N$ | $Q_N/(u_2R_2^2) = 0.63$ |
| Nominal head coefficient $\Psi_N$ | $gH_N/u_2^2 = 0.29$ |
| Nominal rotating speed $n_d$ | 1480 r/min |
| Pressure magnitude $A$ | Pa |
| Pressure coefficient $C_p$ | $A/0.5\rho u_2^2$ |
| Impeller blade number $Z_i$ | 4 |
| Diffuser blade number $Z_d$ | 12 |
| Impeller inlet diameter $D_1$ | 221 mm |
| Impeller outlet diameter $D_2$ | 268 mm |
| Impeller outlet width $b_2$ | 84 mm |
| Peripheral velocity at impeller exit $u_2$ | 20.8 m/s |
| Casing diameter $D_3$ | 637.5 mm |
| Pump hydraulic Efficiency $\eta$ | % |
| Loss of diffuser $\zeta_d$ | % |
| Loss of casing $\zeta_c$ | % |

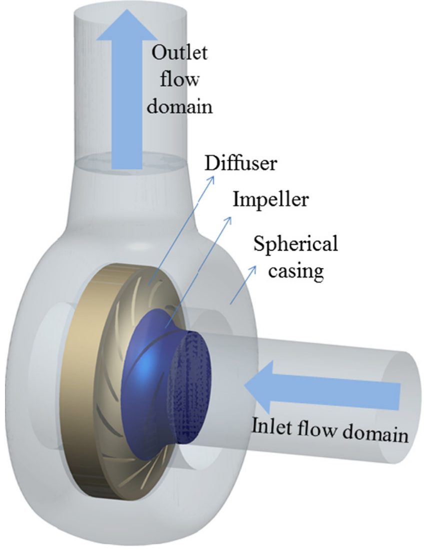

**Fig. 1.** Computational domain of the RCP model pump.