Detailed flow characteristic analysis of a three-stage centrifugal pump at design and off-design conditions

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Abstract. This paper presents a detailed analysis of the internal flow characteristics of a three-stage centrifugal pump at design and off-design conditions. Numerical analysis is conducted by solving three-dimensional steady and unsteady Reynolds-averaged Navier–Stokes equations with the shear stress transport (SST) turbulence model. The results of steady and unsteady numerical analyses are analyzed and compared with experimental data throughout the flow region. Moreover, a reattachment modification in the SST turbulence model is applied to better capture the characteristics of flow separations arising from boundary layers reattaching at design and off-design conditions. The results show that the unsteady numerical results are in good agreement with the experimental data. Additionally, hydraulic performance with and without the reattachment modification is similar throughout entire flow region whereas the respective flow characteristics for each impeller component are considerably different, especially at low-flow-rate conditions.

1. Introduction

Multi-stage centrifugal pumps are typically applied under high-head conditions; for example, as boiler feed pumps, coolant pumps, power plants, and so on. Owing to this extreme operating condition, reliability, durability, and high performance are more necessary for these pumps than for general single-stage pumps. Furthermore, as high-head pumps are especially sensitive to thrust forces produced by their multi-stage impellers, hydraulic design and detailed flow analyses considering these characteristics should be conducted along with installing additional devices such as balance pistons, balance disks, etc.

Recently, Yamashita et al. [1] and Furukawa et al. [2] experimentally measured the radial and axial thrust forces on the entire rotor of a three-stage centrifugal pump. Their results emphasized special thrust force characteristics arising from the axial offset of the rotor over a wide range of flow rates. Watanabe et al. [3] performed unsteady numerical analyses of an identical three-stage centrifugal pump. Detailed internal flow analyses at the design and partial-load conditions were conducted; however, they mostly focused on characteristics of the axial thrust forces and leakage flows in clearance sections for several axial offsets of the rotor.
To expand the existing literature to include internal flow characteristics at design and off-design conditions, this study presents a detailed analysis of an identical three-stage centrifugal pump. The analysis is based on the steady and unsteady Reynolds-averaged Navier–Stokes (RANS) equations with and without the reattachment modification in the k–ω-based shear stress transport (SST) turbulence model.

2. Three-stage centrifugal pump

Figure 1 shows the three-dimensional internal flow computational domain and a schematic diagram of the three-stage centrifugal pump used in this work. This pump consisted of a suction casing, three identical centrifugal impellers, vaned diffusers, two return channels, and a discharge casing. There were seven impeller blades and ten vanes for both the diffuser and return channel. The given specific speed (m, m³/min, min⁻¹) at the operating point was 122. The front and back side gaps of the impeller and impeller–diffuser gap were included and detailed geometrical information can be found in previous works [1–3].

3. Numerical methods

The internal flow field for three-stage centrifugal pump shown in figure 1(a) was analyzed by solving the three-dimensional steady and unsteady incompressible RANS equations with a k–ω-based SST turbulence model using a finite-volume solver provided in the commercial code ANSYS CFX-18.1. In addition, the reattachment modification in the SST turbulence model was applied to better capture the flow characteristics of flow separations arising from the boundary layers reattaching at the design and off-design conditions. In ANSYS CFX, a well-known modification of the standard SST turbulence model can improve its ability to predict reattaching boundary layers. For example, the standard SST turbulence model with the reattachment modification results in significant improvement in the predicted stall mass flow and pressure ratio in the low-flow-rate region for the transonic rotor 35 compressor [4] and other axial compressors [5].

A tetrahedral grid system was constructed in the computational domain with a prism mesh near the surfaces, as shown in figure 2. A grid dependency test was first performed for only the impeller part of the first stage as shown in figure 3(a). Based on the results, a grid dependency test was conducted for the first impeller part including the return channel vane, as shown in figure 3(b), with various numbers of grids. Figure 3 shows the results of the grid dependency test with the normalized total head for the impeller and impeller stage part, respectively. As shown in figure 3, approximately 5.3 million grid points were used to define the first impeller part, including the return channel vane. Finally, approximately 56 million grid points were applied to define the entire computational domain, including the side wall gaps for a three-stage centrifugal pump, as shown in figure 1.

Figure 1. Computational domain and schematic diagram of a three-stage centrifugal pump.
Water was considered as the working fluid and, for boundary conditions, the total atmospheric pressure and a fixed mass flow rate were set at the inlet and outlet of the computational domain, respectively. The solid surfaces in the computational domain were considered as hydraulically smooth under adiabatic and no-slip conditions. The Frozen-rotor and transient-rotor-stator methods were applied, respectively, to connect the interface between the rotating impeller and the vaned diffuser domains in the steady and unsteady analyses.

The convergence criteria in the steady computation consisted of the root-mean-square (RMS) values of the residuals of the governing equations; all the RMS values were set lower than $10^{-4}$ for all equations. The physical time scale was set to $1/\omega$, where $\omega$ is the angular velocity of the impeller. The computations were conducted using an Intel Xeon CPU E5-2630 v2 with a clock speed of 2.60 GHz, and the converged solutions were obtained after 2,200 iterations with a computational time of approximately 18 h.

**Figure 2.** Computational grid system.

**Figure 3.** Results of the grid dependency test.

(a) Impeller component

(b) Impeller part including return channel vane
The results of the steady RANS analysis were used as the initial condition for the unsteady RANS analysis. In the unsteady computations, the time step and the coefficient loop for the time-scale control were set to 0.000208334 s and three times, respectively. The solutions were obtained after 360 iterations with an unsteady total time duration of 0.075 s (two revolutions), and the computational time required for the unsteady calculation was 53 h. The file capacities for the steady and unsteady results were 16 and 22 GB, respectively.

4. Results and discussion

The results of the steady and unsteady RANS analyses were validated by comparison with the experimental data reported in previous works [1–3]. The pump model used in this test was considered as the entire geometry, including the major components and side wall gaps, as shown in figure 1. Figure 4 shows the validation results for the performance curves of the head coefficient and hydraulic efficiency. Here, all parameter values were normalized from their specified corresponding values, respectively. In figure 4, the steady numerical results show some uniform underestimations of the head and efficiency throughout the entire flow rate region compared to the unsteady results and experimental data, whereas the unsteady results are in reasonable agreement with the experimental data. However, all results were quantitatively similar, especially at the design flow rate condition. On the other hand, the results of the steady and unsteady RANS analyses with and without the reattachment modification in the k–ω-based

![Figure 4. Validation of numerical results.](image1)

![Figure 5. Normalized static and total pressure distributions at the design flow rate condition.](image2)
Figure 6. Velocity streamline distribution at the design flow rate condition.

Figure 7. Normalized static and total pressure distributions at low-flow-rate conditions ($\Phi/\Phi_d = 0.2$).

Figure 8. Normalized static and total pressure rise distributions at low-flow-rate conditions ($\Phi/\Phi_d = 0.2$).

SST turbulence model were similar throughout the flow region, as shown in figure 4. Nevertheless, the numerical results using the reattachment modification in the unsteady analyses showed relatively uniform efficiency deviations throughout the flow region compared to the steady results. In other words, the trend of the unsteady results obtained using the reattachment modification was generally similar to that of the experimental data throughout the flow region.
Figure 5 shows the normalized static and total pressure distributions in the steady numerical results with and without the reattachment modification at each component stage at the design flow rate condition. As shown in figure 5, the steady numerical results with and without the reattachment modification were almost identical throughout all stages of the major components of the pump. The modification had no adverse effects on the accuracy of the SST model for weakly separated boundary layers because the main flows at the design flow rate condition were relatively uniform compared to those in the off-design flow region. This result can be also observed from figure 6, which shows the surface streamline distribution in the first-stage impeller with and without the reattachment modification.

Figure 7 shows the normalized static and total pressure distributions at each component stage of the low-flow-rate condition (Φ/Φd = 0.2) in the steady numerical results with and without the reattachment modification. The static and total pressure values at each component stage with and without the reattachment modification were slightly different, as shown in figure 7. In order to analyze in more detail the flow characteristics for the steady numerical results with and without the reattachment modification, the static and total pressure rise distributions were compared at each identical component stage, as shown in figure 8. In the first-stage impeller, the static pressure rise with the reattachment modification was slightly greater than that without the reattachment modification. This phenomenon arises because the reattachment modification reduces the strongly reattached flow’s separation near the blade wall of the impeller. However, the total pressure rise with the reattachment modification was relatively smaller, as shown in figure 8(b). Because of this, the static and total pressure distributions in the downstream components were remarkably different in comparison with the numerical results without the reattachment modification. Additionally, this result can be seen in figure 9, which shows the streamline distribution at the hub surface in the first-stage impeller with and without the reattachment modification. As shown in figure 9, the reattached flow’s separation near the blade wall of the impeller on the regions surrounded by red dotted lines disappeared by the reattachment modification, in comparison with the impeller without the reattachment modification. Consequently, the two methods needed to be verified through comparison with the experimental data at each major component stage because an accurate turbulence model can be important in designing each stage in a multi-stage pump.

5. Conclusions
Detailed analyses of the internal flow characteristics in a three-stage centrifugal pump were performed throughout the flow region. Calculations were based on the steady and unsteady RANS equations with and without a reattachment modification in the k–ω-based SST turbulence model. The main conclusions from this work are summarized as follows.
1) The steady numerical results showed some uniform underestimations of the head and efficiency throughout the flow region compared to the unsteady results and experimental data, whereas the unsteady results were in reasonable agreement with the experimental data.

2) The results of the steady and unsteady RANS analyses with and without the reattachment modification in the k–ω-based SST turbulence model were similar throughout the flow region. Nevertheless, the numerical results obtained using the reattachment modification in the unsteady analyses showed relatively uniform efficiency deviations throughout the flow region compared to the steady results.

3) The steady numerical results with and without the reattachment modification were almost identical throughout all stages of the major components of the pump. The modification had no adverse effects on the accuracy of the SST model for weakly separated boundary layers because the main flows at the design flow rate condition were relatively uniform compared to those in the off-design flow region.

4) The unsteady numerical results with and without the reattachment modification were slightly different at each component stage in the low-flow-rate condition. In particular, in the first-stage impeller, the static pressure rise with the reattachment modification was slightly higher, whereas its total pressure rise was relatively lower, than that in the results without the reattachment modification. This phenomenon arose because the reattachment modification reduces the strongly reattached flow’s separation near the blade wall of the impeller.

5) Because of this phenomenon, the static and total pressure distributions in downstream components were remarkably different in comparison with the numerical results without the reattachment modification. Results needed to be validated through comparison with the experimental data at each major component stage because using an accurate turbulence model can become important in designing each stage in a multi-stage pump.

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