The influence of wall roughness on centrifugal pump performance

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Abstract. Wall roughness is an important factor in the pump head and efficiency. Influence of wall roughness on the performance of a centrifugal pump is conducted with numerical approach. In the present study, a critical value of wall roughness is found. The performance of the pump decreases significantly while the wall roughness is less than critical value and decreases slightly while exceeding it. Influence of wall roughness of each domain is compared; the result revealed that the influence of wall roughness was decreased for volute, impeller, inlet and outlet respectively. Blade wall roughness of impeller has the greatest effect on pump performance, and pressure surface roughness has a greater influence than that for suction surface. This study could provide a reference for the manufacture and design of this type of centrifugal pump.

1. Introduction

Pumps have great applications in industry and agricultural production\cite{1-4}. The washing tower circulating pump, as a centrifugal pump, would transport water mixed with corrosive media during the work process, and corrosion is an important reason for increasing the roughness of the wall surface. The wall roughness has an important influence on the pump efficiency. Therefore, surface treatments of the pump are particularly important.

In the past years, many scholars have studied the effect of wall roughness on flow. The research methods of flow field wall surface roughness are mainly based on experiments and models. Syverud et al.\cite{5} and Kind et al.\cite{6} proposed two calculation models to fit the wall roughness, but their application is still inadequate. Boyle\cite{7} observed the surface microstructure and determined the detailed value of roughness with the instrument test, and then estimated the relationship between $Ra$ and $hs$. Stripf et al.\cite{8} proposed an external heat transfer measurement method for high-load turbine blade surface roughness changes. The results showed that the roughness has a great influence on the transition and the heat
transfer coefficient of the turbulent boundary layer. In the area affected by the secondary flow, the roughness has the most significant effect on the heat transfer, reaching twice the two-dimensional turbulent boundary layer. Montomoli et al. [9] studied the formula for calculating the inner boundary layer thickness theoretically and the results were verified by experiments. Walker et al. [10] studied the influence of surface roughness on the boundary layer on the suction surface of turbine blades. It was concluded that reducing roughness can delay separation of the boundary layer and reduce separation loss while increasing roughness can induce the transition of boundary layer in advance. Yamazaki et al. [11] took the effect of roughness into account when the pump is studied. The results showed that the wall roughness near the throat inlet had the greatest influence on the efficiency of the jet pump. Aldas et al. [12] used numerical calculation to determine the effect of pump absolute roughness and relative roughness on pump efficiency. It was found that when the wall roughness was considered, the efficiency could be significantly improved to a certain degree. Yun and Kim [13] used numerical calculation to determine the effect of pump absolute roughness and relative roughness on pump efficiency. It was found that when the wall roughness was considered, the efficiency could be significantly improved to a certain degree. Zhu et al. [14] studied the influence of wall roughness on flow field characteristics of axial flow pump and the performance difference of axial flow pump under the influence of different wall roughness was obtained through simulation calculation. Lim and Sohn [15] studied the effect of impeller surface roughness on centrifugal pump efficiency by experiment. It was found that the sensitivity of impeller blades to roughness was relatively high. Gu et al. [16] applied an experimental method to investigate the effect of wall roughness on the pump head efficiency and shaft power. The results showed that head and efficiency decreased but shaft power is opposite as roughness increased. Deshmukh and Samad [17] analyzed the influence of turbulent flow energy and eddy viscosity characteristics of electric submersible pumps with different roughness and showed the effect on the pressure distribution and velocity field. It was found that the effect of roughness on performance was different from different medium and Reynolds numbers.

To sum up, wall roughness has a great influence on pump performance. However, there are few studies comparing the effects of the wall roughness of each part of the pump. Due to the limitation of manufacturing method and production cost, high wall roughness of the whole system could not be considered in the actual manufacturing. Therefore, it has great significance to study the effect of wall roughness of each part on the performance of the whole pump.

The paper is organized as follows. Section II provides numerical calculations, including Physics model, Grid validation and Turbulence model. Roughness model is explained in Sec. III. The results of the influence of wall roughness are presented and discussed in detail in Sec. IV. The paper ends with concluding remarks given in Sec. V. The purpose of the article is to provide support for the production and maintenance of this type of pump.

2. Numerical calculations

2.1. Physics model

The presented model is a special centrifugal pump designed for washing tower. The pump is simplified into four domains: inlet, impeller, volute, and outlet. The parameters and schematic diagram of the model are shown in Table 1 and Figure 1.
The design flow rate $Q$ is 18m$^3$/h, and the head $H$ at the design flow rate is 10 m. The impeller inlet diameter $D_1$ is 54mm and outlet diameter $D_2$ is 102mm. The average outlet blade angle $\beta_{2A}$ is 40.5°. The impeller outlet width $b$ is 10mm. The nominal rotation speed is 2900 r/min. The blade number is 6 and the volute diameter $D$ is 110mm.

Table 1. Pump design parameters.

| Parameters       | Value |
|------------------|-------|
| $Q$ (m$^3$/h)    | 18    |
| $H$ (m)          | 10    |
| Rotating speed (r/min) | 2900 |
| $D_1$ (mm)       | 54    |
| $D_2$ (mm)       | 102   |
| $B$ (mm)         | 10    |
| Blade number     | 6     |
| $\beta_{2A}$    | 40.5° |
| $D$ (mm)         | 110   |

Figure 1. General view of the pump model.

2.2. Grid validation

The hexahedral structured grid was generated based on the topology of the pump. To determine the appropriate number of grids, under the same settings, selected 5 sets of different numbers of grids for grid-independent analysis, as shown in Figure 2. It could be seen that when the number of grids reached about 3.5 million, the head was stable, and the calculation requirements have been met. Considering the coordination of calculation accuracy and time, 3.5 million grids were selected as the calculation standard.
2.3. Turbulence model

The selection of the turbulence model is very important in numerical simulation. Generally, different models would have different results, which need to be selected according to the actual situation. In this paper, the calculation results of these models were compared with the experimental values, as shown in Table 2. The results showed that the SST model was in good agreement with the experimental results, so the subsequent numerical calculations in this paper used the SST model.

| Turbulent Models | $\eta$ | $H$ (m) |
|------------------|--------|---------|
| $k-\varepsilon$  | 0.734  | 10.66   |
| RNG $k-\varepsilon$ | 0.723  | 10.45   |
| SST              | 0.712  | 10.39   |
| Experimental value | 0.698  | 10.34   |

3. Roughness model

3.1. Equivalent sand grain roughness model

In actual production, the roughness has peaks and valleys, and the shapes and sizes are different. The technical roughness of peaks and valleys with different shapes and sizes could be described by the equivalent sand roughness ($h_s$). As shown in Figure 3, a rough surface could be equivalent to a sphere with an average height $h_s$ densely spread on a smooth surface.

![Figure 3. Schematic diagram of equivalent sand model](image)

3.2. Wall roughness parameter setting

In previous study, $h_s$ represent the average height of the uniformly laid sand grains in the equivalent sand grain model and this was different from the actual wall roughness (Ra). Moreover, $h_s$ would have a different definite relationship with Ra according to the processing technology and processing method. Adams et al. [19]
proposed an algorithm to convert the measured wall roughness parameters to equivalent sand grain roughness, and used this algorithm to convert the wall roughness to equivalent sand grain roughness and the model was verified by experiments. According to his research, this article determined the relationship as:

$$hs = 5.863Ra$$

For convenience of explanation, the actual wall roughness $Ra$ would be replaced by the equivalent sand grain roughness $hs$. Table 3 is the specific conversion between $Ra$ and $hs$.

| $hs$ ($\mu m$) | $Ra$ ($\mu m$) |
|----------------|----------------|
| 0              | 0              |
| 100            | 17.06          |
| 200            | 34.11          |
| 300            | 51.17          |
| 400            | 68.22          |
| 500            | 85.28          |
| 600            | 102.34         |
| 700            | 119.39         |
| 800            | 136.45         |

### 4. Results and discussion

#### 4.1. Influence of wall roughness on pump performance

To study the influence of wall roughness on the performance of the pump, a total of 9 roughness of 0$\mu m$, 100$\mu m$, 200$\mu m$, 300$\mu m$, 400$\mu m$, 500$\mu m$, 600$\mu m$, 700$\mu m$ and 800$\mu m$ were selected for numerical calculation. The results are shown in Figure 3 and Table 4. It could be seen that there was a critical wall roughness ($hs = 600\mu m$) for the influence of roughness on the performance of the pump. When $0 < hs < 600$, as $hs$ increased, the head and efficiency gradually decreased; when $600 < hs < 800$, as $hs$ increases, the head and efficiency are basically unchanged. When $hs$ increases from 0 to 600$\mu m$, the head decreased by 11.9% and the efficiency decreased by 13.1%. This showed that when the wall roughness was less than the critical wall roughness, the wall roughness had a greater impact on the performance of the pump. While the wall roughness was greater than the critical wall roughness, the wall roughness has little impact on the performance of the pump. It could be concluded that in actual industrial production, the reduction of wall roughness through the transformation of processing methods or the improvement of process level is of great significance to the performance improvement of this type of pump.

| $hs$ ($\mu m$) | 0  | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 |
|----------------|----|-----|-----|-----|-----|-----|-----|-----|-----|
| $\eta$         | 0.782 | 0.722 | 0.713 | 0.703 | 0.696 | 0.689 | 0.651 | 0.647 | 0.646 |
| $H$ (m)        | 11.39 | 10.61 | 10.47 | 10.37 | 10.32 | 10.24 | 10.03 | 9.99  | 9.97 |
It was important to study the reasons of the pump performance variation with different wall roughness and the significance of the critical value. Figure 5 shows turbulent kinetic energy with different wall roughness under the rated flow condition. It could be seen that the turbulent kinetic energy increased gradually with the increase of roughness. The increase of turbulent kinetic energy means that the flow state was more violent and the flow dissipation was larger. Therefore, turbulent kinetic energy increased when the wall roughness increased. When the critical value is reached, the turbulent kinetic energy basically does not change. This indicated that the fluid state was basically unchanged and flow losses increased little when the roughness was more than the critical value.

4.2. Influence of roughness of different parts on pump performance

The decrease in wall roughness means a lower price. In order to decrease price in actual production, only a certain part or some parts are usually smoothed. Therefore, it was necessary to study the influence of wall roughness of different parts on pump performance. In the process of exploring the influence of wall roughness of different parts on the pump performance, this paper controlled $h_{s}$ of other walls to 600µm and the wall surfaces of inlet, impeller, volute and outlet are smoothed ($h_{s} = 0$) respectively. The results are shown in Table 5. It could be seen that the smooth treatment of each part of the wall surface promoted the efficiency of the whole pump, but the roughness of the wall surface of different parts improved the performance of the
centrifugal pump differently. The influence of wall roughness was decreased for volute, impeller, inlet and outlet respectively. Among them, the efficiency and the head increased by 11.1% and 10.2% while the volute wall was smoothed and the efficiency and the head increased by 6.1% and 1.8% when the impeller wall was smoothed. The efficiency and the head increased by 4.4% and 0.59% while the inlet wall was smoothed and the efficiency and the head increased by 3.3% and 0.40% while the outlet wall was smoothed.

Table 5. Pump performance with wall roughness of different part

| Part     | Inlet (hs=0) | Impeller (hs=0) | Volute (hs=0) | Outlet (hs=0) | All rough (hs=600µm) |
|----------|--------------|-----------------|---------------|---------------|----------------------|
| η        | 0.695        | 0.712           | 0.766         | 0.684         | 0.651                |
| H (m)    | 10.09        | 10.21           | 11.05         | 10.07         | 10.03                |

Table 6 shows the pressure difference of different parts. Figure 6 illustrates the variation of pressure difference of different parts. It could be seen that the pressure difference between the inlet and outlet of the volute was relatively small, but the increased amplitude was the largest under the influence of wall roughness. Therefore, the wall roughness of the volute had the greatest influence on the pump performance. The impeller has a characteristic of high-speed rotation and the main energy is converted. So the pressure difference was relatively large. However, the variation of pressure difference is relatively small under the influence of wall roughness. Therefore, the effect of the wall roughness of impeller on the pump performance was not as good as that of volute. This indicated that the effect of roughness on pump performance was mainly related to the flow area.

Table 6. Pressure difference of different part

|              | Inlet    | Impeller | Volute   | Outlet   |
|--------------|----------|----------|----------|----------|
| Rough (hs=600µm) | -2.562e+03 | 1.336e+05 | -3.396e+04 | -1.125e+04 |
| Smooth (hs=0)  | -1.125e+03 | 1.362e+05 | -2.082e+04 | -9.902e+03  |
| Variation     | 1437     | 2600     | 13140    | 1348     |

Figure 6. The variation of pressure difference of different part

4.3. Influence of volute wall roughness on pump performance
The surface roughness of the volute had the greatest influence on the performance of the pump. To study the influence mechanism of the surface roughness of the volute on the performance of the centrifugal pump, the presented study compared and analysed the internal flow of volute between the rough wall and the smooth wall. The central section of the volute was selected as the research object. Figure 7 is the velocity contours of the central section of the volute between the rough wall and the smooth wall. Figure 8 is the total pressure contours of the central section of the volute between the rough wall and the smooth wall.

Figure 7 and Figure 8 showed that the total pressure at the outlet of the volute after smooth treatment was higher than that before, which indicated that the existence of volute wall roughness increased the hydraulic loss of the volute. But the velocity field and total pressure field at the outlet of the impeller were almost unchanged, which indicated that the roughness of the volute wall has almost no influence on the flow field of the impeller. Therefore, the roughness of the volute wall increased the frictional resistance loss caused by the fluid flow in the volute and it could be inferred that part to part would not affect each other by the wall roughness. If the volute wall surface was smoothed and the roughness was reduced, the performance of the pump could be greatly improved without worrying about the flow...
situation in the impeller.

4.4. Influence of impeller wall roughness on pump performance

The impeller of the article was composed of hub, shroud and blade, so it was of practical significance to study the effect of wall roughness of each part on pump performance. Table 7 shows pump performance with wall roughness of different parts of the impeller. It could be seen that the blade wall roughness had the greatest effect on the performance of the centrifugal pump.

Table 7. Pump performance with wall roughness of different part of impeller

| Part | Hub smooth | Shroud smooth | Blade smooth | All rough |
|------|------------|---------------|--------------|-----------|
| \(\eta\) | 0.682 | 0.680 | 0.699 | 0.651 |
| \(H (\text{m})\) | 10.08 | 10.07 | 10.18 | 10.03 |

For blades, different parts had different effects on flows and the performance of the pump on different working conditions would be different. To further study the influence of pressure surface and suction surface roughness on pump performance, the pump head and efficiency at low flow rate(0.8\(Q\)), rated flow(\(Q\))and large flow rate(1.2\(Q\)) were calculated respectively under the design scheme in Table 8.

Table 8. Blade surface roughness design scheme

| Scheme | Pressure Surface \(hs (\mu\text{m})\) | Suction Surface \(hs (\mu\text{m})\) |
|--------|-------------------------------------|-----------------------------------|
| 1      | 600                                 | 0                                 |
| 2      | 0                                   | 600                               |
| 3      | 600                                 | 600                               |
| 4      | 0                                   | 0                                 |

As shown in Figure 9 and Figure 10, both the smooth treatment of the suction surface and the pressure surface could improve the characteristics of the pump, but the smooth treatment of the pressure surface was obviously better. At the rated flow, the head and efficiency increased by about 1.2% and 3.4% when the pressure surface was smoothed while the head and efficiency increased by 0.6% and 1.4% with the smooth suction surface. The former was almost twice as effective as the latter.

Figure 9. Influence of the roughness variation of the pressure surface and the suction pressure surface on the head under different working conditions
Figure 10. Influence of the roughness variation of the pressure surface and the suction pressure surface on the efficiency under different working conditions

Figure 11 is the velocity and total pressure contours of the central section of the impeller of the blade with wall roughness. From Figure 11, it could be seen that the fluid velocity on the suction surface was not high and the fluid pressure was small. When the roughness increased, the shear stress on the surface wall of the blade increased and the velocity decreased, the kinetic energy loss increased, the pressure decreased, and the efficiency decreased. However, due to more larger velocity of pressure surface, so the efficiency dropped more. And the suction surface did little work on the fluid, which could not directly affect the fluid velocity loss. It indicated that the fluid velocity could affect the influence of wall roughness on the pump performance.

Figure 11. Velocity and Total pressure contours of the central section of the impeller of the blade with wall roughness

Conclusions
A numerical study is carried out to investigate the influence of wall roughness on the centrifugal pump performance. The characteristics of pump performance with different wall roughness were studied. The wall roughness influence for each domain is compared separately and the corresponding influence on the pump performance was analysed. The conclusions can be drawn as follows:
(1) Pump head was decreased with the wall roughness increasing, and a critical wall roughness was found. When the wall roughness is less than the critical value, the head and efficiency are greatly decreased. While the roughness exceeds the critical value, the wall roughness process slightly influences on the pump performance.

(2) Different domain with the same critical wall roughness shows a different pressure difference. The influence of each part of the pump is decreased from volute, impeller, and inlet to outlet. The efficiency and the head increase by 11.1% and 10.2% when the volute wall is smoothed. The efficiency and the head increase by 6.1% and 1.8% with the impeller wall smoothed.

(3) Compare with the shroud and hub wall roughness, the blade wall roughness has the greatest impact on the pump head. More specifically, the pressure surface roughness has a greater impact on pump performance than the suction surface roughness and the former is almost twice as effective as the latter.

(4) This study could provide a reference for the manufacture and design of this type of centrifugal pump. In actual processing and production, the performance and corrosion resistance of the pump can be improved by smoothing the wall surface of the volute and the pressure surface of the blade, which can effectively save costs.

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