Study on the effect of the impeller and diffuser blade number on reactor coolant pump performances

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Abstract. In this paper, CFD approach was employed to study how the blade number of impeller and diffuser influences reactor coolant pump performances. The three-dimensional pump internal flow channel was modelled by pro/E software, Reynolds-averaged Naiver-Stokes equations with the k-ε turbulence model were solved by the computational fluid dynamics software CFX. By post-processing on the numerical results, the performance curves of reactor coolant pump were obtained. The results are as follows, with the blade number of the impeller increasing, the head of the pump with different diffuser universally increases in the $0.8Q_n$~$1.2Q_n$ conditions, and at different blade number of the diffuser, the head increases with the blade number of the impeller increasing. In $1.0Q_n$ condition, when the blades number combination of impeller and diffuser chooses 4+16, 7+14 and 6+18, the head curves exist singular points. In $1.2Q_n$ condition, the head curve still exists singular point in 6+18. With the blade number of the impeller increasing, the efficiency of the pump with different diffuser universally decreases in the $0.8Q_n$ and $1.0Q_n$ conditions, but in $1.2Q_n$ condition, the efficiency of the pump with different diffuser universally increases. In $1.0Q_n$ condition, the impellers of 4 and 5 blades are better. When the blade number combination of impeller and diffuser choose 4+11, 4+17, 4+18, 5+12, 5+17 and 5+18, the efficiencies relatively have higher values. With the blade number of the impeller increasing, the hydraulic shaft power of the pump with different diffuser universally increases in the $0.8Q_n$~$1.2Q_n$ conditions, and with the blade number of the diffuser increasing, the power of different impeller overall has small fluctuation, but tends to be uniform. This means the increase of the diffuser blade number has less influence on shaft power.The influence on the head and flow by the matching relationship of the blades number between impeller and diffuser is very complicated, which still need further research.This paper provides a reference for exploring the match relationship between the impeller and diffuser blade number of reactor coolant pump.

1. Introduction

Reactor coolant pump is one of the most important equipment in Nuclear Power Plant. There are many scientific issues which need to be researched in hydraulic components.

Previous researchers have done a lot of work in the pump optimization and the effect of blade number on the pump performance by the numerical simulation. Li Ying [1] used Andritz reactor

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coolant pump of Pakistan's Chashma Nuclear Power Plant as the research object, and got effective access to internal flow characteristics like pressures, streamlines, velocity distributions by numerical simulation. Kim Jin Hyuk [2, 3] adopted numerical simulation method to optimize mixed-flow pump hydraulic components, and finally obtained best internal flow and high hydraulic efficiency. Qin Jie [4] comparatively analysed reactor coolant pump with twisted and diffusion diffuser by numerical simulation, and the results showed that static pressure distribution of twisted diffuser is more uniform. Zhang Dongjun [5] studied the influence of orbicular volute outflow pipe structure on performance of reactor coolant pumps based on CFD method and found out that the conical outlet pipe has better flow characteristics than the cylindrical outlet pipe. Zhu Rongsheng [6] designed 13 kinds of pump chamber outlet shrinking angle to study the influence on pump performance and revealed that the contraction angle has a significant effect on the connection area between pumping chamber and outlet, and as the angle is between 12° and 16°, which the efficiency of the RCP is better. Yan Bipeng [7] researched the influence on pump performance by changing the number of axial-flow pump blades and it turned out that the number of blades affects very little on the efficiency of axial-flow pump but much on its cavitation characteristics. Yang Qiongfang [8] took CFD method principally to investigate effects on the characteristics of flow pattern and water-jet propeller performance when the number of pump blades of both rotor and stator is changed. Eventually, the water-jet optimum performance can be obtained when 5 blades of rotor match 9 blades of stator. Bing Hao [9] simulated the distribution of static pressure and total pressure in the mixed-flow pumps and analysed the consequences of the diffuser vane number, the impeller blade number and the blade thickness on the hydraulic performance of mixed-flow pumps. Wang Xiuli [10] used CFX in the numerical simulation for the radial force variation with the number of blades or diffuser changed and it proved that when the number of blades is 5 and the diffuser is 11, the radial force on the impeller gets the minimum.

This paper summarized the results of previous studies at first, and then used the computational fluid dynamics software CFX to conduct the numerical simulation for reactor coolant pump, and thus analysed the influence on reactor coolant pump performance of different impeller and diffuser blade numbers, and finally provides a reference for the optimize design of the hydraulic model.

2. Numerical Simulation

2.1. The pump basic parameters

According to the parameters of reactor coolant pump, the rated flow is 17886m^3/h, the rated head is 111.3m, the design speed is 1480 r/min, the specific speed n_s is 352.25 ℃ water at 1 atm pressure, volume flow design point Q_n=17886m^3/h converted into mass flow Q_m=4968.3kg/s. Hydraulic components include mixed flow impeller, twisted radial diffuser, and pump casing, which resembles a spherical considering the pressure and operational safety [11]. The geometry model of the impeller, diffuser and pump casing can be established with Pro/E software. The pump three-dimensional structure is shown in figure 1.

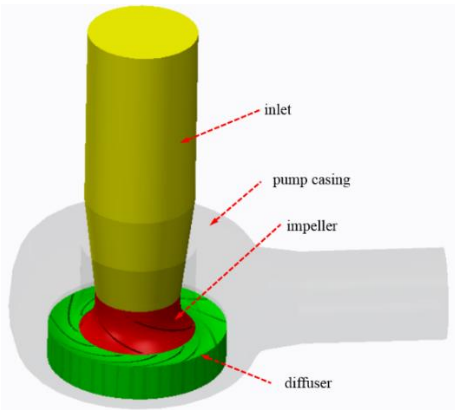


Figure 1. Reactor coolant pump hydraulic component three-dimensional model.

2.2. Match program

Table 1 shows matching relationships of the blade number between impeller and diffuser. The impeller blade number varies from 4 to 7， and the diffuser blade number varies from 11 to18. And 32 different blade number matching relationships between the diffuser and the impeller at a given condition are calculated and the corresponding hydrodynamic performance data is obtained.

Table 1. Matching relationships of the blades number between impeller and diffuser.

Impeller blade number	Diffuser blade number							
4	11	12	13	14	15	16	17	18
5	11	12	13	14	15	16	17	18
6	11	12	13	14	15	16	17	18
7	11	12	13	14	15	16	17	18

2.3. Meshing and grid unrelated test

Use ANSYS-CFX14.5 pre-processing meshing software Workbench to mesh for the model of this study, and take automatic meshing division method to ensure the accuracy of the calculation results. In order to make the number of meshes, the mesh density and the overall quality of grid meet the actual computing requirements, and so that the grid-independent model can be established and researched. The curve graph in figure 2 shows the relationship between the reactor coolant pump head and the number of grids. And it can be obviously seen from the figure, when the number of grid is much more than 3.3 million, the range of variation of the pump head at rated operating point is less than 0.5%, in order to ensure the accuracy of the calculation and the economy, the number of the grids nearly 4.5 million is appropriate.

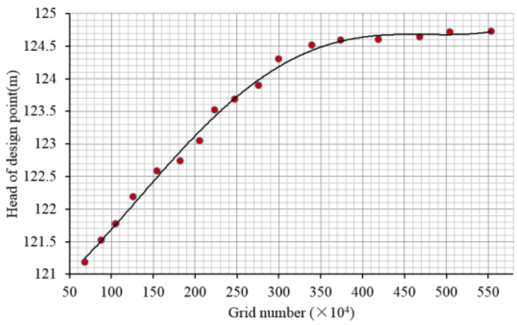


Figure 2. Grid-independent curve.

Figure 3 shows the calculation domain grids of each component. The grid number of the inlet section is 280,612, impeller grid number is 1,638,962, the diffuser grid number is 903,385, the spherical pressurized chamber grid is number 1,930,696, and the total number of grid is 4,753,655.

(a) Assembly Grid (d) Impeller (e) Diffuser

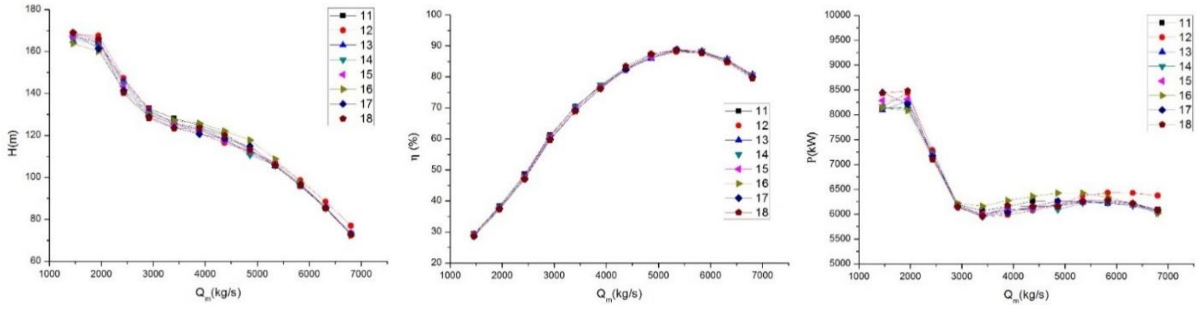
Figure 3. Mesh of each flow component water body and the assembly.

2.4. Boundary Conditions
Reynolds-averaged Naiver-Stokes equations with the k-ε turbulence model were solved by the computational fluid dynamics software CFX. When the flow rate is constant, in order to get more accurate velocity and pressure gradient, pressure-inlet condition is used at inlet, meanwhile using mass-outflow condition at outlet, the mass value determined by the flow, using no-slip wall boundary conditions, movement-static coupling surfaces of the impeller and diffuser, impeller and import section using Frozen Rotor interface. To better handle the flow of the boundary layer, use the standard wall function in the near wall region. Transportation medium is water [12]. Choose default values of CFX software as under-relaxation factors in the calculation process, and the residual convergence precision is set to 10^{-4}.

3. Results and analysis

3.1. The performance curves variation with different impeller and diffuser blade number in different conditions
As shown in figure 4, the head curves variation regular patterns of 4 blades impeller in different conditions are nearly unanimous while diffuser blade number is 11~18. With the flow rate increasing, the head decreases, but the absolute value of the head slope firstly decreases, and then increases, like S-type. The efficiency curves variation regular patterns of 4 blades impeller in different conditions are nearly unanimous while diffuser blade number is 11~18. With the flow rate increasing, firstly the efficiency increases, and then decreases. When Q_m is nearly 5500kg/s, the efficiency reaches the maximum. The power curves variation regular patterns of 4 blades impeller in different conditions are nearly unanimous while diffuser blade number is 11~18. With the flow rate increasing, the power firstly decreases sharply, and then increases slowly until the power curve is smooth, and the power curve is like saddle type. When Q_m is less 2500kg/s, the power reaches to the maximum, and overload phenomenon occurs. That is because the reactor coolant pump hydraulic model is unstable in low flow conditions, and numerical instability leads to the shaft power increasing when the pump operates in small flow conditions. It is obviously in the figures that while diffuser blade number is 11~18, the head curves exist a little difference, which is not clear, and the efficiency and power curses are also like this.

When blade number of impeller changes to 5, 6, 7, variation regular patterns are the same as 4 blade impeller, which are not shown in the paper. But the little differences between the performance curves are researched deeply in following chapters.



(a) The head (b) The efficiency (c) The power

Figure 4. The performance curves of 4 blade number impeller in different conditions.

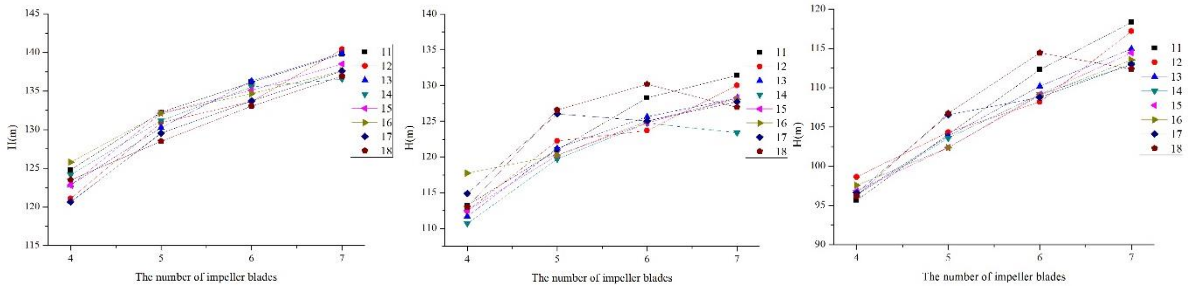
3.2. The effect on the head when only change the blade number of the impeller
As shown in figure 5, with the blade number of the impeller increasing, the head of the pump with different diffuser universally increases in the $0.8Q_n$~$1.2Q_n$ condition, but the head increasing trend slows down. This is because the theoretical head is built by Stodala finite number of blades modified

formula. In the formula, H_t is

$$\mathrm{H_t} = \frac{u_2}{g}\left\{u_2\left(1-\frac{\pi}{z}\psi_2 sin\beta_{2b}\right)-\frac{Q_t}{D_2\pi b_2\psi_2 tan\beta_{2b}}\right\} \tag{11}$$

$$\psi_2 = 1-\frac{Z\delta_2}{D_2\pi}\sqrt{1+\left(\frac{cot\beta_{2b}}{sin\lambda_2}\right)^2} \tag{12}$$

Where H_t is the finite number blade hypothesis theoretical head, u_2 is the blade outlet circumferential velocity, g is acceleration of gravity, Q_t is the flow rate, D_2 is the impeller diameter, b_2 is the blade outlet width, ψ_2 is the crowding coefficient of blade outlet, Z is the number of blade, δ_2 is the thickness of blade outlet, λ_2 is the included angle of axis section transversal and flow line, β_{2b} is the blade outlet angle.



(a) $0.8Q_n$ (b) $1.0Q_n$ (c) $1.2Q_n$

Figure 5. The head curves with the blade number of the impeller increasing.

In Equation 11, substituted into designed impeller geometric parameters, the relation between H_t and Z is shown in figure 6, the theoretical head increases with the blades number increasing, but the head increasing trend slows down. The head variation trend of numerical simulation is consistent with theoretical analysis. But in each condition, there are some differences in the head of different diffuser blade number, and the head changing law is not obvious. This is mainly because the crowding and surface friction at different blades number of impeller and diffuser have great effect on the pump head, and even small changes of the machine geometry may generate big response to the flow and performance.

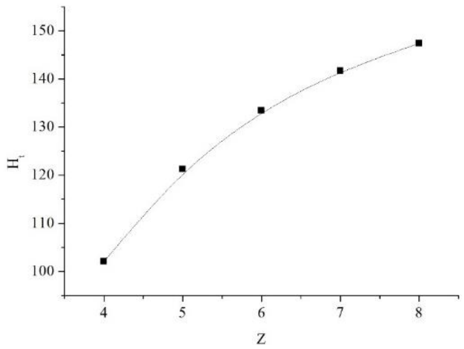
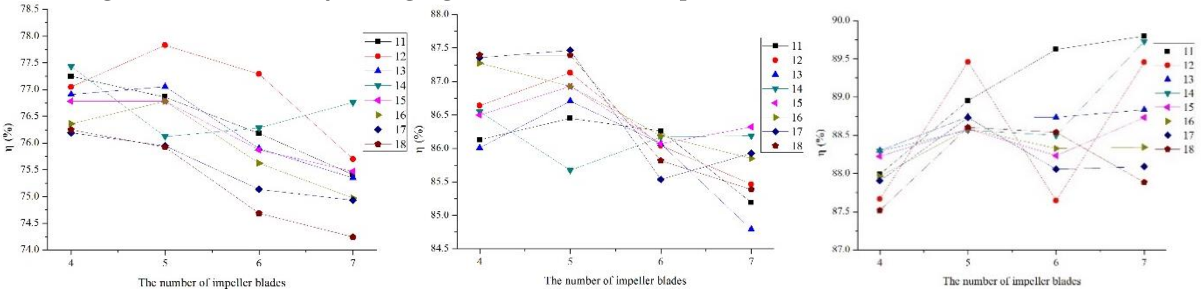


Figure 6. The relation between H_t and Z.

3.3. The effect on the efficiency when only change the blade number of the impeller

As shown in figure 7, with the blade number of the impeller increasing, the efficiency of the pump with different diffuser universally decreases in the $0.8Q_n$ and $1.0Q_n$ condition, and the efficiency changing law is not obvious at different impeller blade number. But in $1.2Q_n$ condition, the efficiency of the pump with different diffuser universally increases with the blade number of the impeller increasing, and the efficiency changing law at different impeller blade number is also not obvious.



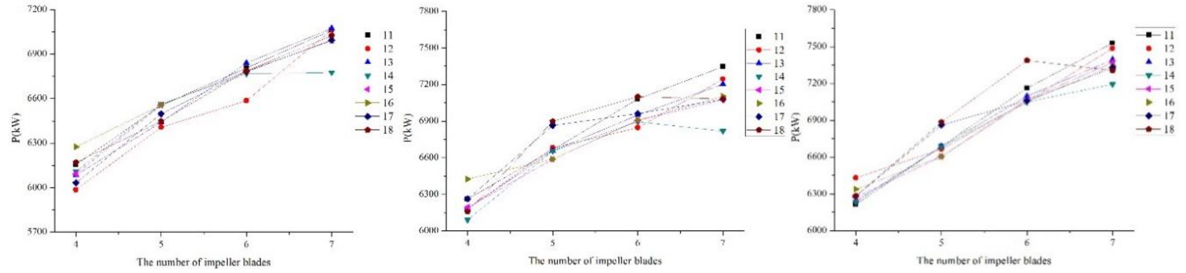
(a) $0.8Q_n$ (b) $1.0Q_n$ (c) $1.2Q_n$

Figure 7. The efficiency curves with the blade number of the impeller increasing.

3.4. The effect on the power when only change the blade number of the impeller

As shown in figure 8, with the blade number of the impeller increasing, the power of the pump with different diffuser universally increases in the $0.8Q_n$~$1.2Q_n$ conditions, and the power changing law at different impeller blade number is more obvious than the head and efficiency.

Figure 5~8 macroscopically reflects the variations of the head, efficiency and power with different blade number of impeller and diffuser, but its performance variation still needs deep analysis.

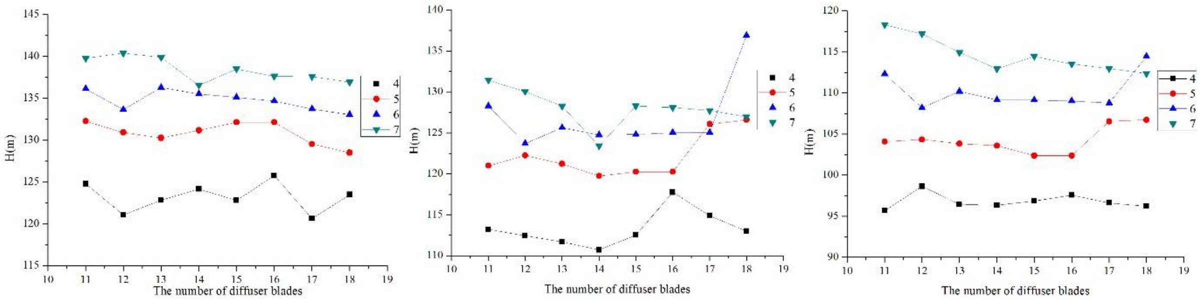


(a) $0.8Q_n$ (b) $1.0Q_n$ (c) $1.2Q_n$

Figure 8. The power curves with the blade number of the impeller increasing.

3.5. The effect on the head when only change the blade number of the diffuser

As shown in figure 9, in $0.8Q_n$ condition, at different blade number of the diffuser, the head increases with the blade number of the impeller increasing, and the head with 7 blades impeller is maximum, the head with 4 blades impeller is the minimum. In $1.0Q_n$ condition, the head changing law is basically same with $0.8Q_n$, but when the blades number combination of impeller and diffuser choose 4+16, 7+14 and 6+18, the head curves exist singular points. In $1.2Q_n$ condition, the head changing law is basically the same as $0.8Q_n$. But when the blades number combination of the impeller and diffuser choose 6+18, the head curve still exists singular point. From the figure 11, it can also be seen that with the increase of the diffuser blades number, the head curve is not linear, nor is a regular curve. In summary, the impact on the head and flow by the matching relationship of the blades number between impeller and diffuser is very complex, which still needs further study.



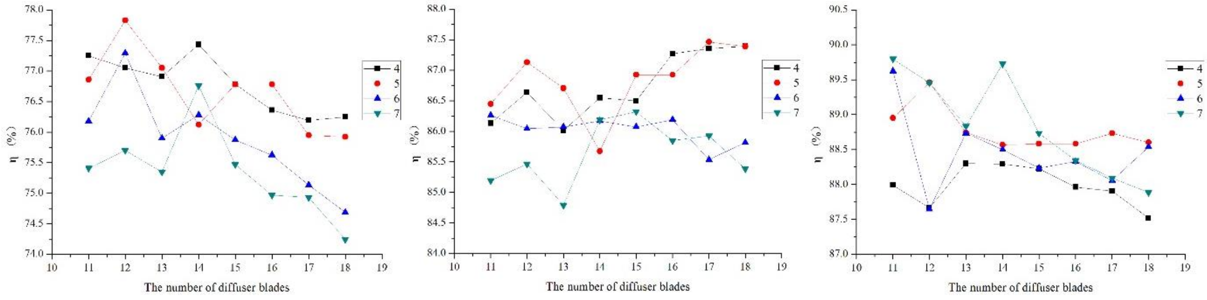
(a) $0.8Q_n$ (b) $1.0Q_n$ (c) $1.2Q_n$

Figure 9. The head curves with the blade number of the diffuser increasing.

3.6. The effect on the efficiency when only change the blade number of the diffuser

As shown in figure 10, in $0.8Q_n$ condition, at different blade number of the diffuser, the efficiency decreases with the blade number of the impeller increasing. And with the blade number of the diffuser increasing, the efficiencies of different impeller overall decrease. When the blades number combination of impeller and diffuser choose 4+11, 5+12 and 4+14, the efficiencies relatively have larger values. In $1.0Q_n$ condition, at different blade number of the diffuser, the efficiency decreases with the blade number of the impeller increasing, the efficiencies of 4 and 5 blades impeller overall show an increasing trend, but the efficiencies of 6 and 7 blades impeller overall show a decreasing trend. When the blades number combination of impeller and diffuser choose 4+11, 4+17, 4+18, 5+12, 5+17 and 5+18, the efficiencies relatively have larger values. In $1.2Q_n$ condition, with the blade number of the diffuser increasing, the efficiencies of different impeller overall decrease. The efficiency changing law is not obvious at different impeller blade number, and the efficiency overall increases with the blade number of the impeller increasing.

At different blades number of the impeller, pump efficiencies fluctuates with changes in the blades number of the diffuser. This is mainly because the efficiency is determined by the head and power, which also fluctuate.

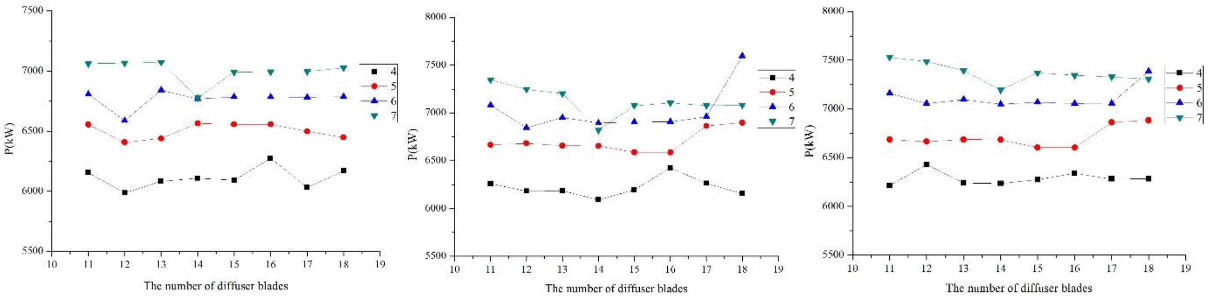


(a) $0.8Q_n$ (b) $1.0Q_n$ (c) $1.2Q_n$

Figure 10. The efficiency curves with the blade number of the diffuser increasing.

3.7. The effect on the power when only change the blade number of the diffuser

As shown in Figure 11, in $0.8Q_n$~$1.2Q_n$ conditions, at different blade number of the diffuser, the power increases with the blade number of the impeller increasing. And with the blade number of the diffuser increasing, the powers of different impellers overall have small fluctuations. This means the increase of the diffuser blade number has less impact on shaft power.



(a) $0.8Q_n$ (b) $1.0Q_n$ (c) $1.2Q_n$

Figure 11. The power curves with the blade number of the diffuser increasing.

4. Conclusion

In this work, the effects of the impeller and diffuser blade number on reactor coolant pump performances are studied with CFD techniques. The following conclusions could be summarized.

(1) With the blade number of the impeller increasing, the head of the pump with different diffuser universally increases in the $0.8Q_n$~$1.2Q_n$ conditions, and at different blade number of the diffuser, the head increases with the blade number of the impeller increasing. In $1.0Q_n$ condition, when the blades number combination of impeller and diffuser choose 4+16, 7+14 and 6+18, the head curves exist singular points. In $1.2Q_n$ condition, the head curve still exists singular point in 6+18.

(2) With the blade number of the impeller increasing, the efficiency of the pump with different diffuser universally decreases in the $0.8Q_n$ and $1.0Q_n$ condition, but in $1.2Q_n$ condition, the efficiency of the pump with different diffuser universally increases. In the design condition, 4 and 5 blades impeller are better. When the blades number combination of impeller and diffuser choose 4+11, 4+17, 4+18, 5+12, 5+17 and 5+18, the efficiencies relatively have larger values.

(3) With the blade number of the impeller increasing, the power of the pump with different diffuser universally increases in the $0.8Q_n$~$1.2Q_n$ conditions, and with the blade number of the diffuser increasing, the power of different impeller overall has small fluctuation, but tends to be uniform. This means the increase of the diffuser blade number has less impact on shaft power.

Acknowledgments

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