Study on the Flow Field in Two-level and Staggered Back Vane and Its Impact on Desulfurization Pump

Yu Zhang *
Institute of Modern Physics, Fudan University, Shanghai, China

*Corresponding author e-mail: yuz@fudan.edu.cn

Abstract. At present, the research on different kinds of the back vane of slurry pumps, such as desulfurization pumps, all focus on simple structures. Many new attempts have been applied in the design of back vane in engineering practice, and the two-layer staggered back vane is one of them. This study analyzes the influence of the new two-layer staggered back vane on the external characteristics, axial force balance, and solid impurities of the desulfurization pump. Based on the steady analysis of single-phase flow, the influence of the two-layer staggered back vane on external characteristics and axial force is studied. It is found that the design of the two-layer staggered back vane has negligible influence on the essential external characteristics of the pump. The design also has the function of balancing the axial force, which is more suitable for the situation that the axial force needed to be balanced is large. Therefore, it supports the two-layer staggered back vane to be widely used in solid-liquid two-phase impurity pumps. Furthermore, the unsteady analysis of two-phase flow is used to study the influence of the two-layer staggered back vane on solid-liquid two-phase flow. It is found that the design without back vane can not prevent the solid phase from depositing between the impeller rear cover and the rear pump cover, which may wear the pump shaft and even block the fluid flow in the rear pump chamber, which may have a severe impact on the mechanical life and performance. The single-layer back vane design can keep the solid concentrating at a low level near the shaft, thus reducing the friction between the solid and the shaft, avoiding the deposition in the rear pump chamber; The two-layer staggered back vane design keeps the solid concentration near the shaft at a lower level and more uniform, and has better protection effect on the shaft, the parts near the shaft, and the rear pump chamber than the traditional structure of the single-layer back vane.

Keywords: staggered back vane; solid-liquid two-phase flow; solid-phase volume fraction.

1. Introduction
Efficient wet desulfurization technology is the leading desulfurization technology. The pump that transports corrosive medium containing fine particles in wet desulfurization devices is called desulfurization pump. The common form of desulfurization pump is cantilever single-stage centrifugal pump, which is generally horizontal pump. Therefore, the structural characteristics of desulfurization pump are similar to those of traditional single-stage horizontal centrifugal pump. When the centrifugal
pump is running at high speed, the liquid will produce an axial force on the impeller, pointing to the inlet of the pump [1]. In engineering practice, back vane can not only balance the axial force of centrifugal pump but also prevent impurities from nearing the bearing, thus prolonging the service life of shaft seal. Therefore, back vane is widely used in impurity pumps.

For axial force balance, Salvadori et al. [2] used computational fluid dynamics (CFD) to predict the axial force of multistage centrifugal pump with balancing drum. It’s found that balance hole will bring the increase of internal leakage loss [3]. In the semi-open impeller, the axial force can be further reduced by removing part of the rear cover plate of the blade [4].

The application of back vane design is an alternative to the above balancing method.

As for the second function of the back vane, Bross[5] said that the back vane pump-out solid particles to reduce the risk of clogging and wear, which is widely used in slurry pumps. By adding back vane, the excessive wear of the seal will be alleviated, which will lead to the increase of seal life and the improvement of pump efficiency.

In the research on the shape and structure of the back vane, Wilk’s [6] research shows the important influence of the tip clearance of the back vane. WANG Yan-fei et al. [7] studied three kinds of Back vane: forward bending, backward bending and straight type. Cao et al. [8] found that the back vane can be used as a secondary sealing mechanism through numerical simulation. As for the two-phase flow of the back vane, the representative work is Tao’s [9], and it focuses on the wear by the solid phase on back vane. Gulich [10] provided a comprehensive elastic standard for the design of traditional back vane.

Study on two-phase flow in pump, K. V. Pagalthivarthi [11] and others used bidirectional coupling and standard k-ε turbulence model to simulate the running of the slurry pump with dilute mud as the medium. Ronnie Russell et al. [12] compared the Discrete Phase Model with the Eulerian-Eulerian Granular Models, and simulated and predicted the erosion and wear of an electric submersible pump. Wang Jiaqiong et al. [13] studied the solid slip velocity and volume distribution based on Particle Model and Heterogeneous Model, and their relationship with the wear of centrifugal pump. Shi Weidong et al. [14] also used the Particle model to study the solid-liquid distribution of swept vane axial flow pumps with different sweep angles. Lin Peng et al. [15] also used the Particle Model, combined with the Heterogeneous Model, to study the solid-phase volume fraction and solid-phase slip on the flow wall in the pump and their effects on the wear of the flow parts of the axial flow pump. Zhang Zichao [16] used the improved resistance model, TE-Wen-Yu model, and the improved sediment diffusion coefficient model DC-PDPC model to simulate the wear of impeller blades of a double suction pump under different sediment concentrations. The study of Guangjie Peng [17] provided a physical experiment on the wear of impurity pump with two-phase flow.

In the field of solid-liquid two-term flow in pumps, a large number of numerical simulation studies are based on Particle Model and Mixture Model, among which Particle Model has been more widely used. According to the definition of Particle Model in the help document [18] of ANSYS-CFX, the solid phase in the two-phase flow is a dispersed medium, so the Particle Model was used for this study.

In this study, the centrifugal desulfurization pump was taken as the research object, and the influence mechanism of the two-layer staggered back vane on the flow field and axial force characteristics of the pump was well demonstrated, which can be taken as the theoretical basis for the optimal design of the back vane. Furthermore, the influence of similar design on the sealing performance such as the two-phase distribution of the transport medium on the back of the impeller, was studied, which has great significance for the design and development of centrifugal pumps transporting solid-liquid two-phase flow, such as desulfurization pumps.

2. Selection of transport medium parameters of solid-liquid two-phase flow and design parameters of the two-layer staggered back vane

In order to make this study representative, it is necessary to select and simplify the transportation medium and process. At the same time, referring to the design method of single-layer back vane, the design parameters of the two-layer staggered back vane were given.
2.1. Transport medium parameters of two-phase flow

Reference [18] was used to determine the physical parameters of the desulfurization medium. The transportation medium was defined as calcium carbonate slurry. The solid-phase volume fraction was set as a typical value of 10%, the particle diameter was set as 58 microns, and there were settings:

| CFX—Pre setting | Molar Mass | Density | Specific Heat Capacity | Specified Point |
|----------------|-----------|---------|------------------------|-----------------|
| solid phase    | 100 kg/kmol | 2930 kg/(m3) | 0 (default) | 25°C |
| liquid phase   | 18.02 kg/kmol | 997 kg/(m3) | 4181.7 J/ (kg·K) | 25°C |

2.2. Selection of design parameters of the two-layer staggered back vane

With careful reference to authoritative monograph book [19] and other related papers, this study gives the selection range of the geometry (including number) parameters of a single back vane: (1) the number of the back vane is greater than or equal to the number of impeller blades; (2) The back vane can be designed as a straight blade or a backward curved blade; (3) Height of back vane $h/r_2 = 0.04 - 0.05$, $r_2$ is the radius of the back vane; (4) Axial clearance of back vane $s/r_2 = 0.01$ or $s/h = 0.2 - 0.05$; (5) width of back vane $t_2$ is about equal to its height $h$.

3. Three-dimensional modeling, grid division, and model pump test

The desulfurization pump in this study corresponds to a product, FMB-NS300, of a Chinese enterprise, and its fundamental design parameters: $Q=1058$m$^3$/h, $H=35$m, rotating speed $n=1450$r/min, impeller diameter $D=400$mm, 5 impeller blades, number of back vanes, $z=10x2$ (10 pairs).

3.1. Three-dimensional modeling

The assembly diagram of the desulfurization pump and its structure diagrams of impeller, back vane, and related water body are shown in figure 3.1 (taking ten pairs of back vanes as an example).

The water explosion diagram and assembly diagram of the whole flow passage of the desulfurization pump are shown in figure 3.2. In the explosion diagram, from left to right, the water bodies are of inlet, impeller, back vane (rear pump chamber), diffusion section, and volute in turn.

**Figure 1.** The assembly diagram of the desulfurization pump & Structure diagrams of impeller, back vane, and related water body
In this study, the numerical simulation variables related to the back vane scheme were divided into 10 kinds: the design without back vane, single layer back vane (10 vanes), two-layer staggered back vane (3 pairs to 10 pairs, 7 kinds). 10 design schemes are shown in the following figure 3.3:

3.2. Grid partition and independence
In this study, the common software, ANSYS ICEM CFD, was used for mesh generation. Tetrahedral unstructured grid technology was adopted to ensure that the grid quality of each computing domain is better than 0.4. Taking the design of 10 pairs of the back vane as an example, the total grid size reaches 15,499,655. And the water body of the impeller with back vane accounts for the largest proportion of the grid number. Each water body was divided into grids with different grid densities. The grid diagram assembled after division is shown in the left figure of figure 3.4 below.

Considering impeller blades have the greatest influence on external characteristics, taking 10 pairs of the back vane as examples, the grid independence of the impeller, as shown in the right figure of figure 3.4, was verified. Four schemes of different grid sizes were compared, and the grid independence test was carried out in the form of single-phase flow under the same standard flow rate.
Table 2. The grid independence test

| Programme | Grid Number | Head H(m) | Efficiency η (%) |
|-----------|-------------|-----------|-----------------|
| Scheme 1  | 5934622     | 36.0255   | 69.2            |
| Scheme 2  | 6278920     | 36.2137   | 69.3            |
| Scheme 3  | 7582250     | 36.2024   | 69.3            |
| Scheme 4  | 11482434    | 36.2077   | 69.3            |

Comparing the four schemes, when the impeller grid number was small, it can't meet the grid encryption requirements of complex positions, and the grid quality can't be guaranteed. And when the grid number was too large, the calculation was slowed. After comprehensive consideration, the Scheme 3 was adopted for the impeller grid number in this study.

3.3. External characteristic test and analysis of simulation effectiveness
The physical model pump of this study and its corresponding back vane are shown in 3.5. In this study, according to the size error caused by the plastic-lined fluoroplastic technology when the enterprise produced the model pump, the corresponding back vane form was drawn. The experiment was carried out based on an informationized test bench of the pump enterprise, as shown in figure 3.6.

To verify the correctness and effectiveness of the simulation method, the simulation flow points in this section were set strictly according to the actual experimental flow points, which are respectively 0.399, 0.593, 0.782, 1.001 and 1.172 times the standard flow. The simulation settings shows in section 4.1. The comparison between simulation data and experimental data is shown in figure 3.7 below.
According to the left figure of fig. 3.7, the average relative error of efficiency at five operating points is 3.46%, and the average relative error of head is 6.5%. It is found that the point with the largest efficiency difference appears at the small flow rate, and the point with the largest relative error of head appears at the large flow rate. Thus, the simulation error of head and efficiency is within the allowable range of engineering. To sum up, the simulation method adopted in this study is effective, and the simulation results are close to reality.

4. Numerical simulation of the two-layer staggered back vane based on single-phase flow
This section analyzes the influence of two-layer of the two-layer staggered back vane on the desulfurization pump's external characteristics and axial force. For the analysis of external characteristics, clear water was chosen as the medium to make a better comparison with previous research results.

4.1. Setting of boundary conditions
The inlet was set as the total pressure inlet, and the boundary condition was set as 1 atm. The outlet was set as mass flow outlet, and the standard flow rate 1.0Qd is 293.889 kg/s. Water bodies of impeller and back vane were set as the rotating domain, and the rotating speed is 1450 rad/min. The other water bodies were set as the static domain; the Frozen Rotor model was adopted to connect rotating and static domains, and None was selected for the connection mode between static domains. Non-slip wall condition was adopted for walls. The mesh connection method was set to GGI. SST was selected as turbulence model. The advection scheme of the solver was set to High Resolution, and the calculation step was controlled by Physical Timescale, which was set to 0.0413793 s. And the convergence accuracy was set to 10 (–4).

4.2. Simulation and analysis of external characteristics of nine different back vane schemes
Six flow points were used to calculate the simulation data, and 1.0Qd is the design flow of 293.889 kg/s. Among the nine schemes of back vane, in addition to the eight newly designed two-layer staggered back vane (3 pairs to 10 pairs), a traditional design without back vane was set as comparisons. Draw the curves of head and efficiency with different numbers of vanes under nine schemes. For the curves of various parameters involved changing with flow rate, the marked 0, 3, 4 ... 10 ( pairs ) represent the different back vane schemes, where 0 represents the traditional design without back vane, and it is the same later.
Figure 8. External characteristic curves in all working conditions

The curves of head and efficiency changing with flow rate under all working conditions were analyzed. It can be found from figure 4.1 that the change rates of head and efficiency with flow rate are basically the same in all nine schemes, and with or without back vane, or the different number of two-layer staggered back vanes does not accelerate or slow down this changing trend.

Figure 9. External characteristic curves near standard working condition

The head and efficiency of different back vane schemes under the same flow point were analyzed. Compared with the traditional design without back vane, all schemes of the two-layer staggered back vane have a certain contribution to the increase of head, but their contribution is not significant. Only in some extreme working conditions, the impact on the head is obvious. At the points nearby standard working condition (1.0 Qd), referring to figure 4.2, the maximum increase of head is 3.4% at 0.8 Qd, 2.6% at 1.0 Qd, and 2.2% at 1.2 Qd.
Compared with the traditional design without back vane, schemes with the two-layer staggered back vane have a negative impact on the efficiency near the standard working conditions, and can have a positive impact on the efficiency when deviating from the standard working condition. The efficiency of different schemes of the two-layer staggered back vane designs are consistently lower than that of the design without back vane near the standard working condition, and the maximum absolute reduction is 1.4% at 0.8 Qd, 1.3% at the 1.0 Qd and 2.1% at 1.2 Qd.

Different vane numbers of the two-layer staggered back vane were analyzed. It can be found that the change of the number of two-layer back vane has no evident influence on the change rate of head and efficiency with flow rate. At standard working condition, the difference between the highest and lowest head is less than 3%, and the difference between the highest and lowest efficiency is about 1%.

To sum up, near the standard working condition, the two-layer staggered back vane only increases the head by about 1%-4%, and reduces the efficiency by about 1%-2%. Thus the existence of the two-layer staggered back vane has little (even negligible) influence on the head and efficiency of the pump.

4.3. Flow fields analysis of single-phase flow for the two-layer staggered back vane

To explain the influence of the two-layer staggered back vane on head and efficiency and the related mechanism, this study selected traditional design without back vane, 4, 7, and 9 pairs of the new designs as representatives, and analyzed the streamline distribution and turbulent kinetic energy distribution at half height of the back vane, and further analyzed the influence of the back vane on head and efficiency.

![Streamline distributions in the pump of 0, 4, 7, and 9 pairs of the back vanes](image)

Figure 10. Streamline distributions in the pump of 0, 4, 7, and 9 pairs of the back vanes

It can be seen intuitively from figure 4.3 that for the design of the two-layer staggered back vane, the back vane has a great influence on the streamline in the gap in rear pump chamber. Compared with the uniform distribution in the design without back vane, although back vanes push the liquid, which makes the steady relative velocity of the flow drop obviously and contributes to the head, they also disturb the flow nearby, and at the same time, produce a lot of vortex flow fields, which makes the flow complicated. With the increase of vanes, the number of small vortices in the rear pump chamber increases. Although the existence of the back vane affects the clearance in the rear pump chamber, obviously, the volute area connected with the outlet of the rear pump chamber is not significantly affected. The interference of the number of vanes on the flow field outside the outlet of the back vane can be obviously weakened in the volute area, and the velocity distribution at the pump outlet is hardly affected by the two-layer staggered back vane. To sum up, it explains why the two-layer staggered back vane design has a little contribution for pump head.
Figure 11. Turbulent kinetic energy distributions in the pump of 0, 4, 7, and 9 pairs of the back vane

Figure 4.4 shows that the turbulent kinetic energy distribution of the design without back vane is quite different from that of the design with the two-layer staggered back vane. The design without back vane relies on Newton's internal friction to drive the liquid to move, which leads to large hydraulic loss of the disk, which shows high turbulent kinetic energy. The two-layer staggered back vane design, in which the back vane does work on the liquid, makes the outlet head of the rear pump chamber larger than that of the design without back vane, which contributes to the head, but makes the outlet flow of the rear pump chamber more complicated. The outlet flows of the back vane and of the impeller may have mutual influence, resulting in larger overall dissipation.

Therefore, the hydraulic loss of the disk in the rear pump chamber is larger in the design without back vane, while the dissipation loss, when outflow from the front and rear pump chambers is mixed into the volute, is larger in the design with the two-layer staggered back vane. It can be seen from the simulation of external characteristics of efficiency that the disk loss is slightly smaller than the mixing dissipation, so both kinds of design have different factors that affect the efficiency. In the end, the efficiency of the design without back vane is slightly higher than that of the two-layer staggered back vane, but the difference is slight. It can be concluded that the design of the two-layer staggered back vane has little influence on the efficiency.

For the two-layer staggered back vane, different number of back vane has little influence on the turbulent kinetic energy distribution in the rear pump chamber. Compared with figure 4.4, the influence of the existence of the back vane on the distribution is near consistent, and the turbulent kinetic energy interference of the flow in the rear pump chamber has little influence in the volute area, until the outlet, this influence almost disappears. Therefore, the influence of different numbers of the back vane on pump efficiency is consistent, and there are little difference between them.

4.4. Study on Axial Force Characteristics of the pump with the two-layer staggered back vane
For nine kinds of back vane, the curve of axial force changing was plotted with the number of vanes, as shown in the left figure of figure 4.5. To explain the influence of the two-layer staggered back vane design on axial force and its related mechanism, in the same way as the above analysis, this section selected the traditional design without back vane, 4, 7, and 9 pairs of the back vane design as representatives to analyze, and the pressure distribution diagrams at half height of the back vane are shown in the right figure of figure 4.5 below.

Analyze the axial force curves under all working conditions in figure 4.5. The variations of axial force with flow rate of nine back vane schemes are similar, and basically decrease with the increase of flow rate. It can be seen from the pressure distribution diagram in figure 4.5 that the two-layer staggered back vane design pushes the liquid, which reduces the steady static pressure of the flow, thus reducing the average static pressure on the back of the impeller. It can also be seen that the influences of different
back vane numbers on the pressure of the rear pump chamber are very similar. With the increase of vanes, the pressure at the rear pump chamber becomes smaller and smaller, especially near the shaft. Consistent with the streamline diagram, the influence of the back vane on the pressure energy of the transport medium cannot be effectively transmitted to the pump outlet.

**Figure 12.** Axial force curves for all working conditions & Pressure distributions of 0, 4, 7, and 9 pairs of the back vane

Generally speaking, the two-layer staggered back vane has the function of balancing axial force, and under design conditions, the more vanes, the smaller the axial force.

5. **Flow fields analysis for the two-layer staggered back vane with solid-liquid two-phase flow**

The above analysis on the influence of the two-layer staggered back vane on pump external characteristics and axial force provides support for the new design to be widely used in solid-liquid two-phase impurity pumps. Furthermore, based on the solid-liquid two-phase distribution, the flow field in the two-layer staggered back vane of the desulfurization pump was studied.

5.1. **Settings of boundary conditions**

The volume flow rate of solid-liquid two-phase flow should be consistent with that of clear water single-phase flow. Regarding the data in table 2.1, the outlet condition of mass flow under standard working condition was set to 351.197 kg/s. Relative settings are shown in table 5.1 below.
Table 3. Main parameters and boundary conditions of two-phase flow

| Parameters                          | Settings                                      |
|-------------------------------------|-----------------------------------------------|
| Two-phase flow medium               | Water and calcium carbonate particles         |
| Dynamics method                     | Eulerian-Eulerian                             |
| Solid-liquid flow model             | Particle                                      |
| Turbulence model                    | Shear Stress Transport(SST)                   |
| Drag coefficient model              | Gidaspow                                      |
| Wall function                       | Scalable                                      |
| Mesh connection method              | GGI                                           |
| Interface connection mode           | General Connection                            |
| Computing domain connection mode    | Frozen Rotor (steady, interfaces between rotating domains and static domains) |
| Inlet and outlet conditions         | Transient rotor stator (unsteady, interfaces between rotating domains and static domains) |
| Advection scheme option             | Bulk Mass Flow Rate (total mass flow rate)    |
| Convergence accuracy                | No-slip wall (wall without slip condition)    |
|                                      | High Resolution                               |
|                                      | $1 \times 10^{-4}$                           |

5.2. Unsteady numerical simulation of solid-liquid two-phase flow

Unsteady numerical simulation method was used to study the movement process of solid calcium carbonate particles in the rear pump chamber and its distribution.

5.2.1. Unsteady numerical calculation method and arrangement of monitoring points. In CFX-Pre, transient was selected as the Analysis Type, and a 3 degree angle of rotating was selected as a time step, which was converted from the pump speed of 1450r/min. Total Time with a value of 0.248276s and Timesteps with a value of 0.000344828s were selected. Accordingly, every 120 time steps is a cycle for impeller rotating. To ensure that the final distribution tends to a relatively stable value, 6 cycles were calculated. The last cycle was selected for quantitative analysis.

Three representative designs of Back vane, design without back vane, single-layer back vane design with 10 vanes, and two-layer staggered back vane design with 10 pairs of vane, were selected for comparison. Unsteady numerical simulation can simulate the dynamic movement process of flow field in fluid machinery basing on time. This function was used to qualitatively and intuitively analyze the "discharge" effect of the back vane on solid phase in solid-liquid two-phase flow. Unsteady numerical simulation can monitor the change of parameters at a particular space point basing on time. This function was used to quantitatively analyze the effect of the back vane on reducing solid volume fraction in two-phase flow.

5.2.2. Dynamic study of solid-liquid two-phase flow distribution. Taking the steady result of solid-liquid two-phase flow simulation as the initial document (which is the average result of relative position with space method and can be used as an initial state to study the subsequent transient motion), the effect of the back vane on the solid phase flowing near the shaft seal was analyzed, and the change of solid-phase distribution basing on time was observed through solid-phase volume fraction.

The solid-phase distribution was plotted by rotating 0, 0.5, 1, 1.5, 2, 3, 4, 5, and 6 cycles. The changes of solid-phase distribution of the three kinds of design with cycles are listed in Table 5.1.
**Table 4.** Solid-phase distribution of the three kinds of design changing with different cycles

| The design without back vane | The single-layer back vane | The two-layer staggered back vane |
|------------------------------|---------------------------|---------------------------------|
| 0 cycle                     | ![Image](image1.jpg)     | ![Image](image2.jpg)          |
| 0.5 cycle                   | ![Image](image3.jpg)     | ![Image](image4.jpg)          |
| 1 cycle                     | ![Image](image5.jpg)     | ![Image](image6.jpg)          |
| 1.5 cycles                  | ![Image](image7.jpg)     | ![Image](image8.jpg)          |
| 2 cycles                    | ![Image](image9.jpg)     | ![Image](image10.jpg)         |
| 3 cycles                    | ![Image](image11.jpg)    | ![Image](image12.jpg)         |
| 4 cycles                    | ![Image](image13.jpg)    | ![Image](image14.jpg)         |
| 5 cycles                    | ![Image](image15.jpg)    | ![Image](image16.jpg)         |
| 6 cycles                    | ![Image](image17.jpg)    | ![Image](image18.jpg)         |

The diagrams listed in table 5.1 directly and clearly show the influence of the three kinds of back vane on the solid volume fraction distribution in the rear pump chamber. The analysis for flow mechanism was carried out according to the flow fields shown in table 5.1.
The design without back vane, at rear pump chamber, relying on Newton internal friction stress of disk wall to drive liquid to make a circular motion. In the process of the motion, at a similar speed, the heavier the medium is, the easier it is to gain more momentum, while the density of calcium carbonate particles is greater than that of water. Because the fluid finally flows to the volute outlet which is near the end of the baffle tongue, the approximate circular variable-speed movement of solid particles has a main acceleration component in the direction pointing to the volute outlet, forming a main flow. In addition, because there is no direct effect of the back vane on the solid particles, the acceleration component brought by the main flow in the pump can easily overcome the centrifugal force, so that the solid with large momentum away from the volute outlet direction squeezer away the liquid and gradually approaches the rotating center. Then, the solid phase gradually fills the area near the shaft away from the volute outlet direction. In this area, careful observation shows that the solid phase is not close to the shaft surface with adhesion. That is, near the shaft wall, the wall friction can well transfer the rotational momentum to the fluid, so that solid particles can obtain more rotational inertia, which leads to the centrifugal force acting in the area near the shaft surface being greater than the acceleration of the above-mentioned main flow, so that the solid phase will not always adhere to the shaft surface. However, due to the relatively significant increase of solid concentration in the near-shaft area, the extent of solid particle impact, the wear of the shaft and the parts near the shaft, and the deposition in the rear pump chamber, is greatly increased. Over time, the life of the shaft and the parts near the shaft and even the mechanical performance of the pump will be seriously affected.

Compared with the design without back vane, the single-layer back vane design can drive the liquid to move circularly by the thrust of the back vane in addition to the friction of the disk wall, so that the fluid near the disk wall can also get the speed close to the impeller speed through the back vane. When the water and calcium carbonate particles get the same moving speed on the thrust surface (the surface pointing to the rotation) of the back vane, the calcium carbonate particles with large density get more kinetic energy. That is, the unit solid-phase volume gets more momentum than the unit liquid-phase volume. And, the ability of fluid resistance to dissipate the momentum of solid components is weaker than that of liquid components. That makes flows with high concentrated solid phase are consistent with rotation in the control body, which is reflected in the diagram that solid-phase distribution changing with time, and that is, the whole red area with high concentration gradually moves away from the center with rotating, while the blue area does not suddenly appear in the center of the red area. The single-layer back vane provides power through the thrust surface of the vane, and the solid phase is subjected to centrifugal force, which can overcome the acceleration component (of the main flow which plays a major role in the flow field in the rear pump chamber in the design without back vane to a great extent) pointing to the volute outlet. Therefore, the solid-phase concentration can be kept at a low level near the shaft, thus avoiding the deposition of the solid phase in the rear pump chamber.

Compared with the single-layer back vane, the two-layer staggered back vane is equivalent to "cutting" and "rotating" the former to the staggered state with an inside circle radius (for example, changing from 10 vanes to 10 pairs of vanes). This new design increases the number of back vane without increasing the manufacturing materials. Its influence mechanism was analyzed below:

As for the single-layer back vane, according to the boundary hypothesis, the fluid obtains the maximum absolute velocity at the back vane and the disk surface of the back vane cover plate, and there is an overall deceleration process at the tip clearance of the back vane (from the axial surface of the back vane to the surface of the rear pump cover) until the absolute velocity drops to zero at the stationary rear pump cover surface. The whole movement trend of solid phase can be divided into a radial outward movement and an axial backward movement (For the cantilever pump, the impeller is at the front end of the shaft, and the motor is at the rear end of the shaft). In the process of deceleration, the influence of centrifugal force on the solid phase, even if the particle is far away from its rotation center, becomes smaller gradually, and accordingly, the radial outward movement weakens.

By comparison, in the staggered back vane design, with the same rotating cycles, the process of pushing by the back vane on the fluid is divided into two sections. Since the wall rotation speed is the maximum speed in the boundary condition, the pushing can be regarded as accelerating the fluid. After
the solid phase accelerates in the inside vanes, according to the above analysis, the flow has the trend of moving radially outward and axially backward (the turbulent movement is complex, and each direction has its own speed, only the large movement trend was considered here), and a certain amount of solid moves axially. These two acceleration processes make the centrifugal force play a dominant role in the solid phase in a small radius range, which makes the concentration of the solid phase near the shaft keep at a lower level and more uniform, and the deposition of the solid phase in the rear pump chamber is fewer. Therefore, the protective effect of the two-layer staggered back vane design on shaft seal and shaft surface is better than that of the single-layer design.

The quantitative verification of above flow mechanism analysis is shown in figure 5.2 below.

![Figure 13](image)

**Figure 13.** Time domain diagram of the solid-phase volume fraction on monitoring points (with sampling fitting, 20 points for each) & The location distribution of monitoring points

To monitor the change of the solid-phase volume fraction near the shaft seal, three monitoring points were set at 40% radius. It can be seen from the time domain diagram of the solid-phase volume fraction that the difference between the high value and the low value of the solid-phase volume fraction is evident during the rotation of the design without back vane. And the trend of the curve corresponds to the rotation process shown in diagrams in table 5.1 of the design without back vane, which forms an excellent mutual confirmation.

**6. Summary**

This study introduced the research background of the back vane, and focused on external characteristics, axial force and solid-liquid two-phase flow, so as to carry out steady and unsteady research based on the designs of the two-layer staggered back vane, the single-layer back vane, and the design without back vane.

(1) Based on the steady analysis of single-phase flow, the influence of the two-layer staggered back vane on external characteristics was studied. It is found that, due to the different mechanism of loss, compared with the design without back vane, the increase of head is less than 3%, and the decrease of efficiency is less than 2% under the standard working condition. Under the standard working condition, the head changes within 3%, and the efficiency changes within 1% when the two-layer back vane are designed with different vane numbers. The design of the two-layer staggered back vane has negligible influence on the basic external characteristics of the desulfuration pump. It provides support for the two-layer staggered back vane to be widely used in solid-liquid two-phase impurity pumps.

(2) Based on the steady analysis of single-phase flow, the influence of the two-layer staggered back vane on the axial force was studied. It is found that the two-layer staggered back vane design has the
function of balancing axial force, which is more suitable for the situation that the axial force to be balanced is too large, and the more the number of blades, the smaller the positive axial force under design conditions.

(3) Based on the unsteady analysis of solid-liquid two-phase flow, the influence of the two-layer staggered back vane on solid-liquid two-phase flow was studied. It is found that the design without back vane will have a serious impact on the life and even mechanical properties of the shaft and its nearby parts if it is used in the desulfurization pump and other impurity pumps. The single-layer back vane design can keep the concentration of solid phase at a low level near the shaft, thus it reduces the friction of solid phase against the shaft and its nearby parts, and the deposition of solid phase in the rear pump chamber. The two-layer staggered back vane design can keep the concentration of solid phase near the shaft at a lower level and more uniform, and the deposition amount of solid phase in the rear pump chamber less, which is superior to the traditional structure of the single-layer back vane in protecting the shaft, components near the shaft, and the rear pump chamber.

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