Erosion predictions of stock pump impellers based on liquid-solid two-phase fluid simulations

Y X Xiao\textsuperscript{1}, B Fang\textsuperscript{2}, C J Zeng\textsuperscript{1}, L B Yang\textsuperscript{3}, F Wang\textsuperscript{2} and Z W Wang\textsuperscript{1}

1. Department of Thermal Engineering& State Key Laboratory of Hydroscience and Engineering, Tsinghua University, Beijing 100084, China
2. Jiangsu Shangbaoluo Pump Industry Co., Ltd. Yangzhou, 225800, China
3. College of Mechanical Electronic Information, Engineering of Beijing Campus of CUMT., Beijing 100083, China

E-mail: xiaoyex@mail.tsinghua.edu.cn

Abstract. Stock pumps cost 25 percent of total power consumption in a modern paper mill. Owing to the severe erosion of pump casing and impeller during operation, stock pump often results in efficiency drop and rising power consumption. A favourable prediction of the impeller wearing character can effective guide optimization design of stock pump impeller. Thereby it can reduce impeller wear and extend stock pump performance life. We simulated the three-dimensional unsteady solid-liquid two-phase flow characteristic in the hydraulic channel of a low specific speed stock pump with open and three blades impeller. The standard $k-\varepsilon$ turbulent model and the pseudo-fluid model were adopted in simulation. Clearance between covers and impeller is taken into consideration in modelling, and pulp is simplified into mixtures of solid particles and water. The Finnie prediction model is applied to predict impeller erosion character. The simulation results of different solid particle size are compared with practical impeller erosion character, and the effects of solid particle size on impeller erosion character are obtained. Thus, numerical method to simulate impeller erosion characteristics of fibered pulp is investigated.

1. Introduction

The stock pump in paper-making process has an important position, and there is a great need of it in papermaking industry of our country. While limited by various factors, the design and study of stock pump of our country lagged distinctly behind other nations, especially the Medium Consistency stock pump. The flow mechanism of paper pulp is extremely complex and is unknown clearly so far. While there are many study works about this aspect, including numerical simulation about the pulp flow in the straight pipe, elbow pipe and pipe with variable cross sections.

As the stock pump is the key equipment of pulp mill, the stock pumps and their parts needed every year are tremendous, especially the flow passage anti-wear components. The severe erosion make the structural material heavily damage, thus influence the operating reliability and stability of the stock pump, which results in efficiency and head drop, service life shorten, replacement and frequently maintenance of the impeller. So study about the erosion character of liquid-solid two-phase fluid to the flow passage components in different working conditions has some guiding significance to the operating, maintenance and design of stock pump. This study is numerical simulations of a centrifugal stock pump based on liquid-solid two-phase fluid method. According the simulation, this study...
analyzed the erosion character of chamber and impeller surface in different pulp consistency and flow rate conditions. Besides, this paper also made comprehensive analysis about stock pump operated in different flow rate conditions.

2. Liquid-solid two-phase numerical simulations

The numerical simulation of two-phase flow regularity is set up on the basis of calculation on clear water field. There are mainly two calculation methods to deal with two-phase flow, Euler-Euler method and Euler-Lagrangian method. This study adopted the latter. In the numerical simulation about erosion character, the paper pulp is simplified into solid particle and the predict model adopted is as follow.

2.1. Abrasion prediction model

Now there are many abrasion prediction models that deal with the problems regarding abrasion caused by the solid particle impact on flow passage components and some typical examples are as follow: the Finnie model; abrasion rate ER model proposed by Ahlert, in which abrasion rate ER is defined as the ratio of abrasion mass in unit area to sediment concentration in unit volume; Turbine abrasion intensity estimation formula that put forward by Nosaki Tsuguo according to a research reference concerning abrasion conditions in Peru’s 18 hydropower stations; Mass wear rate E is defined by Grant and Tabakoff as a way to describe the mass consumption caused by particle in unit mass that impacts on wall surface. This paper adopted the Finnie model.

The abrasion on the wall surface from the solid particles is the function that correlates the particle motion condition, particle characteristics and wall surface characteristics. For most of the metal wall surfaces, the impact angle between abrasion rate and particle is correlated with the velocity and its relation is the Finnie model. The formula for it is as follows:

\[ E_r = k V_p^n f(\alpha) \]  

\[ f(\alpha) = \begin{cases} 
\frac{1}{3} \cos^2 \alpha & \tan \alpha > \frac{1}{3} \\
\sin 2\alpha - 3 \sin^2 \alpha & \tan \alpha \leq \frac{1}{3}
\end{cases} \]  

Among these, \( E_r \) is the abrasion rate which defined as the ratio of target material abrasion mass to the impact particles mass; \( k \) is empirical coefficient; \( V_p \) is the velocity of the particle and \( \alpha \) is the angle between particle motion trajectory and wall surface. The abrasion of solid wall surface can be calculated through formula (3).

\[ E_{rr} = E_r \times \hat{N} \times m_p \]  

When the calculation of the simulation begins, the Finnie model is adopted in the software and many real particles are replaced by single typical particles and \( m_p \) represents the mass of the particles, \( \hat{N} \) represents the number of the particles in unit time and the unit of \( E_{rr} \) is kg/s. When it is in the post-processing period, concept \( \rho_{E_{rr}} \) that represents the density of the abrasion is introduced. \( \rho_{E_{rr}} \) is abrasion rate in unit area and its unit is kg/(s \cdot m^2). As the constant \( k \) of prediction model in various materials is unknown, the abrasion rate for solid wall surface is predicted qualitatively rather than quantitatively.

2.2. Basic pump parameters

The Stock Pump under consideration had a 350 mm diameter impeller. The impeller had 3 opening blades with the blade angle of 175.6 degrees. The height of exit edge of blade is 31 mm. The main design parameters are as follows: flow rate \( Q_0=200 \ m^3/h \), head \( H=32 \ mm \), rotating speed \( n=1450 \ r/min \) and specific speed \( n_s=93 \). The geometrical parameters are as follows: impeller inlet diameter \( D_1=58 \ mm \), impeller exit diameter \( D_2=225 \ mm \), impeller exit width \( b_2=30 \ mm \), base circle diameter of the spiral case \( D_3=280 \ mm \), exit diameter of the spiral case \( D_4=65 \ mm \). The flow media are water and fibered pulp. At the beginning study, the fibre in the pulp are simplified into solid particles to
carry on numerical simulation. Though it different from the reality media and the simulation cannot reflect the real flow pattern of flow field in the stock pump, the simulation results of performance parameters has good agreement with the field test results. Thus, this paper simplified the fibre into roundness solid particle to simulation studies. The flow channel of pump is consist by suction chamber, impeller and casing. And its 3D model is as shown in figure 1.

![Stock pump model](image1)

![Mesh distribution](image2)

There are certain clearance between the impeller and front and back covers. The clearance bigger, its influence on head and efficiency greater. Now it is widely believed that the water flow into the top clearance from the suction surface will accelerate and separate from the top surface of the blade, then re-attach to the top surface at another location. Affected by the leakage flow and secondary flow in the top clearance, it will results in leakage vortex in the blades channel. According to the assembly drawing, the clearance between impeller and front cover set as 1.5 mm and back cover 1.0mm. The computational domain are much more complex while taking the clearances into consideration. The total elements are 680,000 and the nodes are 240,000. The mesh distribution of the whole computational domain is as shown in figure 2.

The numerical calculation adopted the same configuration boundary conditions. Inlet condition: inlet velocity, which is calculated with flow rate and inlet area. Outlet condition: outlet pressure, which is given to a zero average static pressure. The rotated speed of impeller are given by the pump rotated speed, which is 1450 rpm. Wall condition: solid wall set as non-slip boundary condition. Interfaces: the interfaces of suction chamber and impeller, casing and impeller are set as sliding interfaces. The sliding mesh is adopted to simulated the interference of flow field, the mesh of impeller is rotated relative to the mesh of suction chamber and casing, and the two sides’ nodes of interfaces are not coincide, the calculation of each parts are proceeded simultaneously and the velocity components and turbulent at the interfaces required the same after interpolation to ensure the consistencies of integral pressure and flow flux.

2.3. Operating conditions and boundary conditions
The simulated flow rate conditions are 0.4Q₀, 0.6Q₀, 0.8Q₀, 1.0Q₀, 1.2Q₀, 1.4Q₀ and 1.5Q₀. The simulated volume concentration of pulp are 5% and 10%. The velocities were set at the inlet of the pipe with fluid phase velocity set according to the inlet mass flow and the solid phase velocity set to the same velocity as the fluid phase. The average static pressure at the case outlet was specified based on the water level. The wall surface was a rough surface with a roughness of 0.2 mm. The discrete particles were solid with the shape assumed to be spherical. The side wall was considered to have perfectly elastic collisions, collisions between particles were neglected and the influence of particles on the flow field was neglected. The particles were assumed to have a minimum diameter of 0.05 mm,
a maximum diameter of 0.1 mm, a median diameter of 0.08 mm, a standard deviation is 0.02 mm and a particle density of 1,000 kg/m³.

3. Numerical results and analysis

3.1. Erosion character of impeller

This type of pump mainly used in paper mill to deliver low consistency pulp, which is relatively clean. Thus its erosion was mainly caused by fibred pulp. The impeller was made of Gr40 stainless steel. And according to the real operating conditions, the erosion character of impeller was investigated. It is been compared of the erosion of impellers which have operated for different period with the new impeller in the figure 3. Figure (a) was a new impeller, figure (b) was an impeller running for one month and figure (c) was an impeller running for eight months which was scrap for its heavy erosion.

![Figure 3. Erosion for the impeller blade](image)

As can be seen from the field erosion character of impeller, the blade surface was quite smooth, which was got worn of the low consistency pulp. The abrasion surface appeared some typical fish-scale patterns. Compared the different erosion character of impeller, at the beginning phase, the impeller erosion was happened at the pressure surface near the exit edge of blade. The two edge on the pressure surface near the exit edge was firstly rounded off, especially the exit edge place which can be seen from figure 3(b). After long time wearing by pulp, the exit edge of blades were almost gone and the erosion of pressure surface was the most severe. At the same time, the head and suction surface of blades have varying degrees of wearing. For the whole pump, the erosion of impeller and front cover were the most severe abraded, while the back cover and casing was the next more severe.

3.2. Influence of clearance on the pump hydraulic performance

To deliver the pulp unblocked, the impeller of stock pump was commonly open. The clearance of covers and impeller has a great impact on the hydraulic performance. The figure 4 showed the numerical performance curves while the pump deliver water. The simulation models used were model regardless of clearance and model taking the clearance into consideration. According to the curves, the high efficiency area of pump appeared among the 0.8Q₀ and 1.0Q₀. The model with clearance has relatively lower efficiency rate and head than the model regardless of clearance. The main reason was the loss of flow from the top and bottom clearances with the backflow and eddy in clearances, which mainly result in hydraulic loss. The hydraulic performance was great influenced by the size of clearances. In this simulation, the top clearance was 1.5 mm and bottom clearance was 1 mm, which leads to a 12% efficiency rate loss and 5 m head drop in the design condition, while the shaft power was almost same.
3.3. Abrasion characteristics for various pulp concentration

The liquid-solid two-phase fluid simulations can be used to predict the abrasion distribution character on impeller and pump body surfaces. The numerical results can reflect the total wear rate and the maximum wear rate limit on the surfaces. While the relative wear rate can be defined as wear rate divide by the maximum limit. As the constant $k$ of prediction model in various materials is unknown, the relative wear rate for solid wall surface is predicted qualitatively rather than quantitatively. And the figure 5 shows the varying results, as discharge varying, of the relative wear rate of casing, blades, front cover and back cover at two different pulp consistency conditions. The relative wear rate bigger, the erosion at this place more severe, and vice versa.

As shown in the two figures, the relative wear rate changing curves of each component are higher in the figure (a) than in the figure (b), which means with pulp volume concentration increases, the relative wear rate increases and indicates that the higher pulp volume concentration will aggravate the abrasion of flow passage components. The purple changing curves in figure 5 indicates the relative wear rate of casing surface increases at the beginning, then decreases with discharge growing. The maximum rate appears between the $0.5Q_0$ and $0.7Q_0$, at that discharge the backflow in the stock pump is severe and the efficiency rate is relatively low. While with discharge growing, the backflow from casing tongue gradually fades away, which will results in higher efficiency rate and less abrasion. Analyzing the change of the red curves, the minimum relative wear rate of blades surfaces appears between the $0.8Q_0$ and $1.0Q_0$ in the lower concentration condition and appears at $1.0Q_0$ in the higher concentration condition. And with the discharge condition departures, the relative wear rate increases. The blue changing curves show the relative wear rate of front cover reaches a maximum limit at a small discharge condition and remains invariant at the discharge condition of $0.9Q_0$ to $1.5Q_0$. The olive-green curves implies the minimum relative wear rate of back cover appears in the high efficiency
rate area and are lower while compared with other curves, which means the relative wear rate of back cover is smaller than the other components. In all, the relative wear rate of casing surface and impeller surface are relatively higher.

3.4. Abrasion distribution characteristics for various discharge

The liquid-solid two-phase fluid simulations can directly analyze the relative wear rate on the impeller surface. The figure 6 and 7 are the abrasion distribution characteristics of impeller surface and solid particle streamline numerical results for same pulp concentration, but various discharge. The figure 6 shows the abrasion distribution results of impeller for pulp concentration of 5%. According to the figure 5 the higher concentration condition has similar abrasion variation characteristics to the lower condition. So this part of study only presents the results of concentration of 5%. The (a)–(h) represent the results of 8 different discharge conditions. All the figures have the same scale, using the different color to represent wear rate. Because the simulation was stationary calculation, the relative position of blades and casing tongue would influence the abrasion distribution results on each blade. The followed studies would adopted the unsteady calculation. Each figure has the same impeller position. As can be seen from the numerical results, the abrasion area and intensity of 3 blades are not the same in any figure. Therefore, the predicted abrasion area of 3 blades denote the whole possible abrasion area on the blades surface in the field condition.

![Figure 6. Abrasion characteristics of impeller for various discharges (concentration of 5%)](image)

Based on the abrasion prediction of impeller for various discharges, the seriously worn area mainly distributes on the pressure surface at its exit edge and the two edges near the clearances. The abrasion characteristics of pressure surface differs for various discharges. Under the small discharge conditions, the three edges near the exit of impeller have relatively more severe abrasion. Under the 0.6Q₀ condition, the tail part of all three blade pressure surface suffers heavy erosion. Under the design discharge condition, abrasion area on the three blade pressure surface is relatively the smallest. As discharge grows, the heavily worn area expands from the edges of tail parts to the two whole up and down edges of pressure surface and the abrasion area gradually expands too. Unlike the pressure surface, the abrasion of suction surface is relatively less severe and the abrasion area of it mainly distributes at the face of it (unlike the edges of pressure surface). The heavily worn area also changes for different discharges and its distribution on the suction surface of the three blades are not the same.
In the case of whole blade surface, it is relatively most severe worn under the small discharge condition of \(0.6Q_0\), relatively least serious under the design discharge condition. As the discharge departs from the design position, the abrasion of impeller surface would aggravate.

The figure 7 shows the simulation results of stream lines of solid particles in the impeller field for various discharges with pulp concentration of 5%. The (a)–(h) represent numerical results of 8 different discharge conditions with the same scale that use the color change indicate the velocity change of stream lines. In the figures, the relative location of impeller are same to that of figure 6.

![Stream lines of solid particle for various discharge (concentration of 5%)](image)

**Figure 7.** Stream lines of solid particle for various discharge (concentration of 5%)

According to the results of flow distribution, the leakage flow between the two blade flow fields clearly appears under the consideration of clearances of impeller and covers in simulation. And the solid particle also have some leakage flow in the clearances. Corresponding to the abrasion area in figure 6, the stream line results show a relatively concentrated solid particle leakage flow, at the seriously worn area on pressure surface, namely the three edges near the tail. The solid particles clash and impact the edges of blades, thereby it results in abrasion. However, the erosion of suction surface is relatively less severe and the abrasion area of it mainly distribute on the surface which has a significantly different with pressure surface. The stream line results indicate distinct vortex flows near the abrasion area on the suction surface. At the same time, the solid particle leaked from the clearance is easy to form vortex due to the turbulence. This vortex would clash the suction surface and the clash place changes for various discharge, but it distributes at the surface far from the edges.

The numerical predicted abrasion area of impeller mainly distribute at the three edges near the exit on pressure surface, on the whole surface of suction surface and the head of blade also has certain degree abrasion. The numerical results has good consistency of the erosion case at the different phase of the field test photographs. Via the numerical calculation for various discharge conditions, this paper analyses the hydraulic reasons of impeller surface abrasion of open stock pump. At the different abrasion area, the abrasion intensity is decided by the flow characteristics of the flow field nearby. In the case of pressure surface, the solid particle leakage flow caused by clearance makes the solid particles directly clash and impact the two edges of pressure surface. So this place has the most severe abrasion. Compared with the photographs of real impeller (figure 3), this area would be gradually rounded off after long time operating. The clearances scale also progressively increase and make the leakage flow from it more serious. Therefore it results in more severe abrasion. The whole tail part would gone as operating time passed which is shown in figure 3(c). While in the case of suction...
surface, the vortex in the flow field accompany with the backflow of leaked solid particle would clash the face of suction surface. And the clashed place changes for various discharges. In all, the abrasion on the whole face of suction surface is relatively less severe and more balanced than pressure surface.

4. Conclusions
The simulations was used to investigate the internal flow of stock pump for various discharge and different pulp concentration. This study mainly predicts the abrasion characteristics of the impeller and casing surface and finds out the hydraulic reason of the surface abrasion of impeller. The conclusions are as follows:

1. This study conducts analysis of the abrasion characteristics of the whole passage components of stock pump in detail. It finds out that the relative wear rate increases as pulp concentration grows. For a certain pulp concentration, the abrasion is relatively most serious under $0.6Q_0$ condition and least severe under the design condition. As the discharge depart from design point, the abrasion of passage components gradually grow severe. In the four passage components, the predicted abrasion of impeller and casing surface are relatively most severe.

2. The predicted abrasion distribution characteristics of impeller surface has good consistency of the erosion case of the real impeller. The most severe abrasion area appears at the three edges near the exit on pressure surface. While the abrasion of suction surface distributes on the whole face.

3. With the combination of the field photographs and numerical simulation based on liquid-solid two-phase fluid, this study gives a detailed analysis of internal flow characteristics of stock pump. It found out the hydraulic reason of surface abrasion of impeller are as follows. In the case of pressure surface, the solid particle leakage flow caused by clearance makes the solid particles directly clash and impact the two edges of pressure surface. So this place has the most severe abrasion. While in the case of suction surface, the vortex in the flow field accompany with the backflow of leaked solid particle would clash the face of suction surface. And the clashed place changes for various discharges. In all, the abrasion on the whole face of suction surface is relatively less severe and more balanced than pressure surface.

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