Numerical Simulation Of Propellant Slurry Stirring Process

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Abstract—Taking the mixing process of medicine slurry in kneader as the research object, the finite element analysis method was used to simulate the law and characteristics of TCM slurry flow in the mixing process. The simulation results show that the telocentric blade plays an important role in the stirring process. The scraping area of telecentric blades and the kneading area of two blades are the main kneading areas. The flow direction of slurry does not change at different speeds, and the velocity has a linear relationship with the blade speed. The axial conveying capacity is the best at the central horizontal section of the mixing kettle. When the rotational speed increases, the shear stress and viscous heat loss rate increase, and the viscosity decreases.

1. INTRODUCTION
Solid propellant is a kind of high-energy composite material. In the process of manufacture, there are many unsafe factors, such as combustion or explosion, especially the mixing process, as the key process of charge production, is of great significance to ensure the safety of production. At present, twin-blade planetary kneader is widely used to mix slurry at home and abroad[1]. The velocity, shear stress, viscosity and other parameters of propellant slurry in this process have been studied extensively by scholars at home and abroad. Tanguy[2] confirmed that twin-blade planetary kneader combined axial and radial motion and could reduce the mixing time by 30% at the same mixing power. Kresta&Wood[3], Fokema[4] collected the fluid velocity change data in the stirred tank, and established a 3D mixing model based on the rotating blade model to predict the mixing situation in the real stirred tank. Tang Hanxiang[5] studied the effects of AP gradation and aluminum powder on the rheological properties of HTPB propellant slurry and the rheological properties of aluminum powder /HTPB suspension by means of experiments. Wang Jiajun[6] studied the motion in fluid mixing by means of LDV and CFD, and measured the parameters of velocity field and concentration field in the mixing kettle.

Liu Zuohua[7,8] eliminated the isolated mixing regions in the stirred tank, and studied the factors associated with chaotic mixing performance. Luan deyu[9,10] studied the dynamic characteristics of impeller of perturbed six-bent-bladed turbine in pseudoplastic fluid based on fluid-structure interaction. In this paper, the mixing process of slurry in the mixing kettle of twin-blade planetary kneader is taken as the research object, and the flow characteristics of slurry in the mixing kettle are studied by using the finite element analysis method, which can provide theoretical reference for the safety research of solid propellant slurry mixing process and the analysis of mixing performance.
2. MATERIALS AND METHODS

2.1. The physical model
The schematic diagram of the mixing kettle area and the geometric model of the blades are shown in Figure 1 and Figure 2.

Figure 1. schematic diagram of the mixing kettle area

I: kneading zone; II: scraping wall area III: blade zone; IV: no-blade zone

Figure 2. Geometric model of blade

2.2. Blade motion and slurry parameters
In order to compare the mixing law at different stirring speeds, the stirring at two speeds was simulated. At high speed, the blade revolution speed is 7.385 rpm, the rotation speed of the proximal blade is 30rpm, and the rotation speed of the telecentric blade is 60rpm. Under the condition of low speed, the rotation speed of the blade is 1.477 rpm, the rotation speed of the proximal blade is 6rpm, and the rotation speed of the telecentric blade is 12rpm. The difference between the two speeds is five times. The revolution is clockwise, and the direction of rotation of the telecentric blade is the same as that of revolution, while the direction of rotation of the proximal blade is the opposite.

The Herschel-Bulkley model is used for the constitutive model of the slurry, assuming that the slurry is a viscous fluid, regardless of its elasticity. The material parameters of the slurry are: critical stress $\tau_c = 20\text{Pa}$, Power law exponent $n = 0.8$, Viscosity coefficient $K = 2000\text{Pa} \cdot \text{s}$, Critical viscosity $\mu_0 = 2000\text{Pa} \cdot \text{s}$, Density $\rho = 2100\text{kg} \cdot \text{m}^3$.

3. NUMERICAL SIMULATION RESULTS AND ANALYSIS
Two sections $z=0.015\text{m}$ and $z=0.05\text{m}$ were respectively taken to analyze the velocity, shear rate, viscous heat loss and viscosity.

3.1. Velocity analysis
The corresponding phase angles at the time $t=0.2\text{s}$ (low speed) and $t=0.04\text{s}$ (high speed) were respectively taken to analyze the velocity distribution under low speed and high speed. The velocity distribution diagram of the two sections is shown in Figure 3.

It can be observed from the velocity diagram that at low speed and high speed, the flow states of the propellants at the corresponding sections are basically similar, but the flow velocity at the corresponding high speed is approximately 5 times that at low speed. It can be considered that increasing the blade rotation speed only improves the flow velocity of propellants, and has little change in the flow direction of propellants.
Figure 3. Horizontal section velocity profile
Since the rotation direction of the blade is the same as that of the revolution, the motion of the blade is the superposition of rotation and revolution, while the rotation direction of the blade is opposite to that of the revolution, the velocity of the blade should be subtracted from the velocity of revolution. Therefore, in the process of stirring, it is the telocentric blade that promotes the drug blade movement.

The maximum velocity region on the same section appears in the blade tip near the wall of the telecentric blade, where is the superposition of the rotation speed and revolution speed of the telecentric blade in the same direction, which is the fastest part on the section of the two blades. At the telecentric end of the paracentric blade, the rotation direction of the blade is opposite to the direction of revolution, which also plays a role in promoting the slurry flow, but the slurry flow in the whole basin is mainly clockwise under the push of the paracentric blade. There is a large velocity gradient in the wall scraping area and the kneading area of the two blades, which is the main kneading area in the mixing process.

Figure 4 shows the axial velocity distribution of \( z = 0.015 \text{m} \) and \( z = 0.05 \text{m} \) sections \( v_z \) at \( t = 0.2 \text{s} \) under the condition of low velocity.

Under the influence of the helix Angle of the blade, the slurry is pushed up on the windward side of the blade to produce an upward speed, while the leeward side produces a downward speed. The \( z \) velocity reflects the axial circulation capacity, and the axial flow rate reflects the axial transport capacity of the agitator blade. The greater the axial flow, the better the axial circulation effect, the better the mixing effect.
Figure 5 is the axial flow curve of different horizontal sections at the same phase Angle under two rotational speeds. It can be seen that the axial conveying capacity is best at the central horizontal section of the mixing kettle. The distance between the central horizontal section and the bottom of the mixing kettle is 0.35m.

3.2. Shear rate analysis

High shear rate can improve the dispersion and mixing ability of the stirring process. Figure 6 shows the shear rate distribution at different sections. The high shear rate mainly exists in the kneading area and the scraping area. The maximum shear rate appears at the tip of the distocentric blade and the other extreme value appears in the kneading area. This is mainly because there is no slip condition on the wall surface and the slurry velocity is zero, while the maximum velocity of the flow field is at the tip of the propeller. The distance between the tip of the propeller and the wall is very small, so there must be a large velocity gradient and shear rate.

Most of the region around the proximal impeller shows a low shear rate. With the progress of revolution, the slurry in the region of low shear rate is driven to the region of high shear rate, so that the polymer components and solid particles in the slurry are fully mixed. The motion of the blade can ensure that the motion path and motion range of the slurry in the kneader continuously pass through the high shear zone, so that the slurry can be dispersed repeatedly under shear. The repeated scraping of the wall and the cleaning effect of the kneading of the two paddles can quickly scrape off the slurry adhered to the wall and send it back to the high shear zone, thus achieving good heat transfer performance.
3.3. Viscous heat loss analysis

The region with high shear rate is also the main region of viscous friction heat generation, and the heat generation in the stirring process is mainly concentrated in these regions. Figure 7 shows the distribution of viscous heat consumption in the stirring process. Under the condition of high rotational speed, the viscous heating increased significantly, the rotational speed increased by 5 times, and the viscous heat consumption rate increased by about 18 times. It can be seen that the increase of rotational speed has a great influence on the rise of temperature in the process of stirring and has a great influence on the safety performance of stirring.
Figure 7. Horizontal section viscous heat loss rate profile
3.4. Viscosity analysis
In the actual situation, the change of slurry viscosity is determined by many factors, which is also a very complex process, among which the shear rate and temperature have the greatest influence on viscosity. In this paper, the simulation time is very short and can be considered as an approximate isothermal process. According to the cross-section viscosity distribution figure 8 and shear rate distribution Figure 6, the viscosity of the slurry changes with the change of shear rate. In the high shear rate region, strong shear thinning behavior occurred and viscosity decreased significantly. In the kneading area of the two blades, because of the different rotation directions of the two blades, the motion direction of the slurry at the blade boundary is opposite, which will also form a large shear rate and lead to shear thinning. The thinning of shear reduces the resistance of blade rotation and is beneficial to stirring. The maximum dynamic viscosity occurs in the region far from the near core impeller and close to the kettle wall, where the slurry flow performance is the worst and the shear rate is the lowest. The smallest dynamic viscosity is found in the kneading region and the wall scraping region of the telecentric blade, corresponding to the region with high shear rate.

It can be seen from the viscosity distribution of slurry at different sections in figure 8 that the viscosity of slurry at the higher section position is lower, mainly because the higher the position is, the better the flow condition of slurry is, and the distribution of high shear rate is wider than that at the bottom.

![Viscosity distribution](image)

(a) low speed, \( z=0.015\text{m}, \ t=0.2\text{s} \)

(b) low speed, \( z=0.05\text{m}, \ t=0.2\text{s} \)
Under the same phase angle at two rotational speeds (low speed $t=0.2s$, high speed $t=0.04s$), the average viscosity of the slurry in the mixing kettle was obtained through the statistics of the whole flow field. The average viscosity was $536.2 \text{ Pa} \cdot \text{s}$ at high speed and $749.3 \text{ Pa} \cdot \text{s}$ at low speed. The shear rate is higher at higher speeds than at lower speeds, so the viscosity distribution is lower than at lower speeds.

4. CONCLUSIONS

(1) In the process of stirring, the telecentric blade plays a major role in promoting the movement of the propellants. Increasing the rotation speed of the propellants only improves the flow speed of the propellants, but has little change in the flow direction of the propellants. The scraping area of the telecentric blade and the kneading area of the two blades are the main kneading areas. The axial conveying capacity is the best at the horizontal section in the center of the mixing kettle.

(2) When the rotational speed increases, the shear stress level increases by about 3.6 times, and the viscous heat consumption rate increases by about 18 times, which has a great influence on the temperature rise in the stirring process and the safety performance of stirring. The increase of rotational speed increases the shear stress, which increases the dangerous degree of slurry mixing.

(3) The maximum dynamic viscosity occurs in the region far from the proximal blade and close to the kettle wall, the smallest dynamic viscosity is found in the kneading area and the scraping area of the telecentric blade. The viscosity of the slurry is lower in the higher section. The viscosity distribution decreases with the increase of rotational speed.

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