Flow field simulation of grain milling based on fluent

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Abstract. In order to study the flow field characteristics and pressure distribution in the grinding chamber during the working process of the grain milling machine of the grain mill, explore the influence of different working parameters of the milling mechanism on the milling effect, and study the use of Fluent to move the milling mechanism. The numerical simulation of the grinding flow field under different working parameters such as 750 r/min, 1000 r/min, 1500 r/min and feeding speeds of 0.5 kg/min, 0.75 kg/min and 1 kg/min were carried out. The results show that the dynamic pressure contour in the flow field is distributed in a ring shape, and its value increases as the radius of the grinding disc increases and the disc gap decreases. When the shape of the grinding disc changes, the dynamic pressure value will increase sharply, that is, the pressure of the powder particles increases, and it is more likely to be broken. Therefore, the shape of the grinding disc can be changed to increase the dynamic pressure and improve the grinding effect. When the disc clearance is 0.05 mm, the optimum grinding effect is obtained when the rotating disc speed is 1500 r/min, and the maximum grinding speed is between 0.5 kg/min and 0.75 kg/min.

1. Introduction

Disc milling is the main processing method for grain flour. Due to its high production efficiency, suitable grain types, small product size, convenient operation and stable operation, it is widely used in the field of grain milling [1, 2]. When the grinding disc is working, the change of its various operating parameters not only affects the production efficiency, but also affects the powder quality, particle size, even taste. The parameter related to the particle size of the powder is that the particle flow field forms dynamic pressure during milling. Therefore, it is necessary to study the dynamic pressure distribution in the working area of the grinding chamber and its relationship with the operating parameters such as grinding wheel speed and feeding speed, and to explore the optimal operating parameter combination to ensure the quality of the grain powder.

With the development of computational fluid dynamics, numerical simulation began to be applied to the analysis of flow field in powder processing [3]. The computational fluid dynamics method is to simulate the fluid motion state under the control of the basic equation of the flow through computer calculation, so as to obtain the distribution law and variation form of each physical quantity in the flow field, which has the characteristics of high calculation efficiency and short cycle [4-6]. In this study, Fluent is used to numerically simulate the material flow field in the working area of the disc-type grain mill, and the visualization results of the flow field in the working area under different working conditions are obtained, and the optimal working state is determined.
2. Principle of disc milling

Figure 1 shows the structure of the disc mill. The milling process mainly includes a pretreatment section and a grinding section. The main function of the pretreatment part is to drive the blade to rotate at a high speed by cutting the motor, and cut the material into coarse material for fine grinding. After that, the cutting motor is reversed and the coarse material is conveyed to the refining system for fine grinding by a vertical feed screw. The refining system consists of a grinding chamber, a fixed grinding disc fixed to the frame, and a rotating disc rotating at a high speed. The material passes through the screw conveying action, enters the gap between the two grinding discs from the center of the fixed grinding disc, rotates at high speed together with the moving grinding disc, and generates radial movement due to centrifugal force, while the gap between the two grinding discs decreases in the radial direction with increasing radius, thereby generating pressure on the material, causing the material to be broken into fine powder, and the fine powder is scooped out under the action of rotating centrifugal force to complete the milling process [7-9].

![Figure 1. Schematic diagram of the grain mill.](image)

Note: 1- cutting motor; 2- cutting tool; 3- vertical feeding screw; 4- horizontal feeding screw; 5- fixed grinding disc; 6- moving grinding disc; 7- main motor.

3. Fluid turbulence model selection

During the milling process, the grains are pre-treated (crushed by blade) and high-speed extruded to completely fill the gap area of the disc. Therefore, the particle flow in the grinding area can be regarded as a one-way flow. Moreover, during the grinding process of the grains, there is interaction force between the materials, and the force increases with the decrease of the grinding disc gap, the momentum transfer between the materials, and the material flow system is the mass conservation, the density of the material increases with increasing pressure, so this grinding process can be considered as compressible unsteady turbulent flow. The governing equations involved are: continuous equations, momentum equations and turbulence model equations [10]. The RNG k-ε model is one of the turbulence model, it accurately handles high strain rates and large turbulent bending flows, which is suitable for the flow field simulation of this test [11, 12]. Therefore, the RNG k-ε two-equation model is chosen as the turbulence model established in this study.

Continuous equation:

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0
\]  

Momentum equation:

\[
\rho \frac{du}{dt} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left[2\mu \frac{\partial u}{\partial x} - \frac{2}{3}\mu \text{div}(u)\right] + \frac{\partial}{\partial x}\left[\mu \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] + \frac{\partial}{\partial z}\left(\mu \frac{\partial v}{\partial z}\right)
\]
\[
\rho \frac{dv}{dt} = -\frac{\partial p}{\partial y} + \frac{\partial}{\partial y} \left[ 2\mu \frac{\partial u}{\partial y} - \frac{2}{3} \mu \text{div}(u) \right] + \frac{\partial}{\partial x} \left[ \mu \left( \frac{\partial u}{\partial x} + \frac{\partial v}{\partial x} \right) \right] + \frac{\partial}{\partial z} \left( \mu \frac{\partial v}{\partial z} \right)
\]  

RNG two-equation model:

\[
\frac{\partial}{\partial t} (\rho k) + \frac{\partial}{\partial x_i} (\rho ku_i) = \frac{\partial}{\partial x_j} \left( \alpha_k \mu_{ij} \frac{\partial k}{\partial x_j} \right) + G_k + \rho \varepsilon - Y_m + S_k
\]  

\[
\frac{\partial}{\partial t} (\rho \varepsilon) + \frac{\partial}{\partial x_i} (\rho \varepsilon u_i) = \frac{\partial}{\partial x_j} \left( \alpha_k \mu_{ij} \frac{\partial \varepsilon}{\partial x_j} \right) + C_{\mu \varepsilon} \frac{k}{\kappa} (G_k + G_s + G_h) - C_{\mu \varepsilon} \frac{\varepsilon^2}{k} - R_\varepsilon + S_\varepsilon
\]  

\[
\mu = C_{\mu} \frac{\rho k^2}{\varepsilon}
\]  

Where: \( \rho \) is the material density; \( \mu \) and \( \nu \) are the components of the fluid velocity in the \( x \), \( y \) directions; \( t \) is the time; \( k \) is the turbulent flow energy; \( \varepsilon \) is the turbulent dissipation rate; \( G_k \) is the turbulence generated by the laminar velocity gradient Kinetic energy; \( G_b \) is the turbulent flow energy generated by buoyancy; \( Y_m \) is a wave due to the fluctuation of transition diffusion in compressible turbulent flow; \( C_{1\varepsilon} \), \( C_{2\varepsilon} \), \( C_{3\varepsilon} \) and \( C_{\mu} \) are constant; \( \alpha_k \) and \( \alpha_\varepsilon \) are the turbulent Prandtl number of \( k \) equation and \( \varepsilon \) equation; \( \mu_t \) is the turbulent viscosity.

4. Numerical simulation

4.1. Determination of main parameters of milling mechanism

4.1.1. Structural and operating parameters of the milling mechanism. According to the actual parameters of the grain mill and related calculations, the relevant parameters related to this experiment are determined. According to the parameters of common industrial three-phase motors, three common speeds of 750 \( r/min \), 1000 \( r/min \) and 1500 \( r/min \) are taken. Combined with the previous test data, the milling speed of the mill is about 0.5-1 kg/min, so take 0.5 kg/min, 0.75 kg/min and 1 kg/min as the three feed rates. Results in Table 1 imply that the final structural parameters and operational parameters.

| Parameter Type                  | parameter |
|---------------------------------|-----------|
| Grinding disc inner diameter    | 35        |
| Grinding disc outer diameter    | 75        |
| Grinding disc clearance         | 0.05      |
| Grinding disc speed             | 750/1000/1500 |
| Feeding speed /kg/min           | 0.5/0.75/1 |

4.1.2. Calculation of the working area of the grinding disc. As shown in Figure 2, the cross section of the grinding disc is simplified when it is working. Because the grinding disc gap is much smaller than other dimensions. For the convenience of calculation, the grinding disc gap is zero. It is assumed that the material is simplified and the material is calculated as spherical particles with radius \( r \).

Then:

\[
r = s \sin \left( \frac{\alpha - \beta}{2} \right)
\]  

\[
L = \frac{D}{2} - s \sin \left( \frac{\pi - \alpha - \beta}{2} \right) - t
\]
Where: \( D \) is the outer diameter of the grinding disc; \( L \) is the inner diameter of the theoretical particle flow field; \( r \) is the radius of the material particle; \( \alpha, \beta \) is the dynamic grinding disc, the working surface of the fixed grinding disc and the axis; \( t \) is the plane width of the outer edge of the grinding disc.

From Equations (7) and (8), \( L \) and \( s \) can be obtained, and the remaining parameters can be directly obtained. Therefore, the flow field structure parameters of the milling mechanism can be obtained according to the particle size of the material.

![Figure 2](image-url)  
**Figure 2.** Working section of the milling mechanism.  
Note: 1- dynamic grinding disc section; 2- fixed grinding disc section; 3- material particles; 4- grinding disc central axis.

### 4.1.3 Material simulation parameters

By consulting the literature and experiments, results in Table 2 imply that the material parameters [13].

| Parameter Type            | parameter       |
|---------------------------|-----------------|
| density /kg/m³            | 750             |
| specific heat capacity /J/ (kg·K) | 2000           |
| Thermal Conductivity /W/ (m·s) | 0.0454         |
| Viscosity /Pa·s           | 0.001005        |

### 4.2 Modeling and meshing

The calculation area needs to be pre-processed before using Fluent for calculation. Firstly, according to the parameters determined by 3.1 calculation, the calculation area is modeled by Pro/E software, then the established model is imported into ICEM CFD for mesh division. And define the inlet and outlet of the simulated particle flow field, the contact surface of the fixed grinding disc and the material, the moving disc and the material contact surface. Through multiple pre-simulations, it is finally determined that the hexahedral meshing method is used to improve the mesh precision, and the total number of meshes is divided into 19,740.

### 4.3 Simulation parameter setting and calculation method of related values

In order to ensure the accuracy and convergence of the simulation, a pressure-based solver, SIMPLE algorithm, and second-order upwind style solution are used [14].

The correct setting of boundary conditions is a vital part of Fluent analysis. When meshing in the pre-processing, the inlet and outlet of the particle flow field, the fixed grinding disc and the material contact surface, the moving disc and the material contact surface have been named by ICEM CFD. In addition, specific parameters need to be set in Fluent. For inlet conditions, Fluent offers three
conditions for speed inlet, pressure inlet and mass inlet [14]. In this study, the inlet pressure is uncertain and the inlet flow is certain, so the quality inlet condition is selected. For the required turbulent flow energy and turbulent dissipation rate, it can be obtained by Equation (9) and Equation (10).

\[ k = 1.5 \times (u_{avg})^2 \]  \hspace{1cm} (9)

\[ \varepsilon = \frac{C_{mn}^{0.75} \cdot k^{1.5}}{0.07l} \]  \hspace{1cm} (10)

Where: I is the turbulence intensity, take I=5%; \( u_{avg} \) is the average speed; \( c_{mn} \) is a constant, take 0.09; \( l \) is the entrance feature size.

In order to solve the convergence problem, the outlet type selects the pressure outlet condition, and the turbulent flow energy and turbulent dissipation rate can be calculated by Equation (9) and Equation (10). Since the research involves the rotary motion of the grinding disc, the surface of the moving disc is set to rotate, and the central axis of rotation is the axial direction of the moving disc. And the surface of the two grinding discs is set to no slip condition. When the residuals of each variable involved in the simulation calculation are less than or equal to \( 3 \times 10^{-3} \), the calculation result is considered to be convergent.

5. Numerical simulation results and analysis

5.1. Distribution of the flow field in the grinding chamber

Under the condition of the grinding disc rotation speed of 750 r/min and the feeding speed of 0.5 kg/min, the flow field of the powder particles in the working area of the grinding chamber is numerically simulated. The radial interface dynamic pressure contour of the working area of the grinding chamber is shown in Figure 3.

![Figure 3. Dynamic pressure contour of flow field pressure in grinding chamber (Pa).](image)

It can be seen from Figure 3 that the dynamic pressure in the flow field obtains the minimum value at the minimum radius, and as the radius of the grinding disc increases, the dynamic pressure increases continuously, and the dynamic pressure is distributed in a ring shape in the working area of the disc. It can be seen from Figure 4 that the dynamic pressure on one side of the dynamic grinding disc is slightly larger than the side of the static grinding disc at the same radius level, but in the overall trend,
the dynamic pressure distribution in each radial section of the flow field is almost the same. It can be inferred that by analyzing the dynamic pressure distribution of the contact surface with the material on the dynamic grinding disc, the dynamic pressure distribution of the whole working area can be obtained, and the grinding effect of the grinding mechanism under the corresponding working conditions can be inferred.

**Figure 4.** Dynamic pressure contour of flow field pressure in radial section of grinding cavity (Pa).

In order to visually study the relationship between the dynamic pressure distribution and the radial size in the flow field of the working area of the grinding chamber, the dynamic pressure values of each radial position are extracted from the contact surface of the moving disc and the material, and the dynamic pressure curve is generated, as shown in Figure 5.

**Figure 5.** Radial dynamic pressure distribution curve of the powder particles along the moving disc.
It can be seen from the graph that in the 40-72 mm stage, the dynamic pressure increases with the radius and the disc gap decreases, and it rises smoothly. In the 72-73 mm phase, the dynamic pressure rises sharply. Since the diameter of the grinding disc is 75mm, the width of the outer surface of the grinding disc is t=3mm. As can be seen from Figure 2, the outer diameter of the moving and grinding disc is changed at 72mm, and the shape of the moving and static grinding disc changes here. The sudden change in pressure is caused by a change in the direction of the particle velocity of the material. By observing the velocity vector chart shown in Figure 6, it is found that the direction of the moving speed of the material particles here has changed, and at the same time, the speed is reduced. So it is speculated that when the material particles change in the size of the grinding disc, the collision angle with the surface of the grinding disc increases, so that the collision movement of the material particles and the wall surface is intensified, and the dynamic pressure is increased. The increase of dynamic pressure helps the crushing of the powder. Therefore, when designing the grinding disc structure, the shape of the contact surface of the grinding disc and the material can be changed to change the flow velocity of the material, increase the dynamic pressure, and thereby improve the effect of the grinding powder.

Figure 6. Velocity vector chart for particle flow field at 72mm.

5.2. Influence of rotational speed on pressure field distribution
When the feeding speed is 0.5 kg/min, the numerical simulation of the working area of the grinding mechanism under the three operating conditions of grinding disc rotation speeds of 750 r/min, 1000 r/min and 1500 r/min is carried out. Figure 7 shows the dynamic pressure contour of the surface of the grinding disc. Figure 8 shows the radial dynamic pressure distribution curve of the powder particles along the moving disc.

From the Figure 8, the maximum dynamic pressure is 4.44 kPa, 7.51 kPa and 13.5 kPa when the rotational speed of the dynamic grinding disc is 750 r/min, 1000 r/min and 1500 r/min. With the increase of the rotational speed of the dynamic grinding disc, the dynamic pressure level on the grinding disc also increases, and the slope of the dynamic pressure curve is continuously improved, that is in the working condition of 1500 r/min, the dynamic pressure increases fastest in the working area of the grinding chamber, which indicates that the increase of the rotational speed has a large influence on the grinding effect. And it is inferred that the working condition of the rotating disc rotation speed is 1500 r/min, which has a better milling effect.
Figure 7. Dynamic pressure contour of the surface of the grinding disc with different rotating speeds (Pa).
Figure 8. Radial dynamic pressure distribution curve of the powder particles along the moving disc at different rotating speeds.

Figure 9. Dynamic pressure contour of the surface of the grinding disc with different feeding speeds (Pa).
5.3. Influence of feed rate on pressure field distribution

In the working condition of the rotating disc rotation speed of 1500 r/min, the numerical simulation of the working area of the grinding chamber with the feeding speed of 0.75 kg/min and 1 kg/min respectively is carried out. Figure 9 shows the dynamic pressure contour of the surface of the grinding disc. Figure 10 shows the radial dynamic pressure distribution curve of the powder particles along the moving disc.

![Dynamic Pressure Distribution](image)

**Figure 10.** Radial dynamic pressure distribution curve of the powder particles along the moving disc at different feeding speeds.

From the Figure 10, the maximum dynamic pressures of feeding speeds of 0.5 kg/min, 0.75 kg/min and 1 kg/min are 13.5 kPa, 13.9 kPa and 14.3 kPa, respectively. The maximum dynamic pressure has a certain range with the increase of feeding speed, but the increase is not obvious. In the three working conditions, the maximum dynamic pressure is only increased by about 3% when the feed rate is increased by 50% and 33%, respectively. In the region of radius 40-72 mm, the magnitude and growth rate of dynamic pressure are negatively correlated with the feeding speed, and the dynamic pressure is under the two conditions of feeding conditions of 0.75 kg/min and 1 kg/min respectively. The growth rate is relatively close. Combined with the experience summarized in previous experiments: appropriate increase in feed rate can increase the milling speed of the mill. It is inferred that when the feeding speed reaches 0.75 kg/min, the milling speed of the grinding mechanism has reached the maximum, and the particle velocity in the grinding chamber grows slowly, thereby reducing the increase of dynamic pressure. It can be further speculated that the increase of feed rate has a little influence on the milling effect, but from the perspective of milling speed, the optimum feeding speed is between 0.5-0.75 kg/min.

6. Conclusions

(1) Combining the theory and practical experience, the paper analyzes the material flow characteristics of the grain-type milling and establishes relevant mathematical models.

(2) The simulation results show that the dynamic pressure contour in the flow field is distributed in a ring shape, and its value increases as the radius of the grinding disc increases and the disc gap decreases.

(3) When the shape of the grinding disc changes, the direction of the flow field changes, the collision between the particles and the grinding disc is intensified, and the dynamic pressure will rise sharply with the sudden change of the dynamic pressure. The increase of the dynamic pressure will help the crushing of the powder, in other words, there is a good material pulverization effect in this area.
Therefore, when designing the grinding disc structure, the shape of the contact surface of the grinding disc and the material can be changed, the flow velocity of the material is changed, the dynamic pressure is increased, and the effect of the grinding powder is improved.

(5) The comparison experiment shows that in the scope of investigation, when the grinding disc gap is 0.05 mm, the dynamic grinding disc speed is 1500 r/min, the best grinding effect is obtained. At this time, the maximum grinding speed is between 0.5-0.75 kg/min, that is feeding speed should be controlled between 0.5 kg/min and 0.75 kg/min.

References
[1] Tao Z D and Zheng S H 2010 Powder Engineering and Equipment (Beijing: Chemical Industry Press) pp 62-71
[2] Zhang Y Z and Qi Q M 2007 Food Processing Technology and Equipment (Beijing: China Light Industry Press) pp 119-191
[3] Yang J G, Zhang Z Y, Yan X L and Tan J Y 2010 Engineering Fluid Dynamics (Beijing: Peking University Press) pp 286-309
[4] Shuli T, Peng W and Qi Z 2011 Analysis of fluid energy mill by gas-solid two-phase flow simulation Powder Technology 208 684-693
[5] Zhou J J, Xu G Q and Zhang H J 2010 FLUENT engineering technology and case analysis (Beijing: China Water Resources and Hydropower Press) pp 1-38
[6] Li J L, Li C X and Hu R X 2010 FLUENT 6.3 flow field analysis (Beijing: Chemical Industry Press) pp 12-18
[7] Yao J and Wang P 2012 Measurement and adjustment method of disc grinding disc gap China Paper 31 67
[8] Zhang C S, Cheng J H, Wu Q S and Li Y H 2007 Powder Technology and Equipment (Shanghai: East China University of Science and Technology Press) pp 80-81
[9] Beshada E, Bux M and Waldenmaier T 2006 Design and Optimization of a Photovoltaic Powered Grain Mill Science Translational Medicine 6 1601-1608
[10] Zhang K P, Tan C and Zhang F W 2016 Fluent-based wheat roller milling flow field simulation and experimental verification Journal of the Chinese Cereals and Oils Association 31 11-18
[11] Hadziabdic M, Hanjalic K and Mullyadzhanov R 2013 LES of turbulent flow in a concentric annulus with rotating outer wall International Journal of Heat and Fluid Flow 43 74-84
[12] Shen P Y, Zhao H and Zhang Y Z 2010 Numerical Simulation and Experiment of High-speed Cutting and Crushing Flow Field of Agricultural Products Journal of Agricultural Machinery 41 60-65
[13] Li X Y, Cai G P and Tian X W 2018 Numerical simulation of the flow field in the grinding chamber of em type coal mill Coal Technology 37 315-318
[14] Dong L, Johansen S T and Engh T A 1994 Flow-Induced by an impeller in an unbaffled tank.2. Numerical Modeling Chemical Engineering Science 49 3511-18