Numerical analysis of temperature field in the high speed rotary dry-milling process

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Abstract. For the effect of the temperature field in the ceramic dry granulation. Based on the Euler-Euler mathematical model, at the same time, made ceramic dry granulation experiment equipment more simplify and established physical model, the temperature of the dry granulation process was simulated with the granulation time. The relationship between the granulation temperature and granulation effect in dry granulation process was analyzed, at the same time, the correctness of numerical simulation was verified by measuring the fluidity index of ceramic bodies. Numerical simulation and experimental results showed that when granulation time was 4min, 5min, 6min, maximum temperature inside the granulation chamber was: 70℃, 85℃, 95℃. And the equilibrium of the temperature in the granulation chamber was weakened, the fluidity index of the billet particles was: 56.4, 89.7, 81.6. Results of the research showed that when granulation time was 5min, the granulation effect was best. When the granulation chamber temperature was more than 85℃, the fluidity index and the effective particles quantity of the billet particles were reduced.

1. Introduction

At present, the raw material of building ceramic bodies were mainly made by wet ball-milling technology, the high energy consumption, serious pollution and other problems do not conform to the environment protection policy which was made by the country [1]. Building ceramic billets dry granulation technology could solve such problems fundamentally, but the building ceramic bodies still had some problems, such as irregular surface shape, high hardness and other defects. These problems will lead to some bad consequences, such as ceramic body forming process easily stratified, low intensity, surface roughness and so on [2-3]. Temperature will affect the plasticity of ceramic bodies in a certain extent. Especially, when the temperature exceeded 80℃, the plasticity of ceramic bodies would be greatly damaged [4].

The author established the dry granulation test platform and found that: the temperature of the granulation chamber’s wall rose quickly in the dry-milling process. In order to find the relationship between temperature field and granulation effect in dry granulation process, the author combined experimental data to establish the three-dimensional physical model of dry-milling granulation chamber which based on computational fluid dynamics method [5] to simulated and analyzed the pattern between the temperature field and granulation time. It effectively controlled the dry granulation time to prevent the damage of billet particles, improved the dry milling granulation effect and provided theoretical guidance for the further promotion of dry milling technology in building ceramics industry.
2. Model establishment

2.1. Mathematical model
The size of the building ceramic materials before granulation was the um level, it could be assumed that the building ceramic materials, as the same as quasi-fluid phase, when the temperature field mainly rose in the mixing stage, only the internal granulation chamber had air phase and powder particle phase. The initial particle size distribution of the powder particles accounted for about 1/4 of the volume in the granulation chamber, therefore, the air phase was selected as the main phase and the powder particle phase was selected as the secondary phase. The mathematical model of the temperature field of dry milling process was established by Euler - Euler model [6-7]. In the iterative calculation process, air phase and powder particles coexisted and permeated each other. Their speed, volume distributions were relatively independent. The air-phase and powder-particle phases had their continuity equations, momentum conservation equation and the energy conservation equation [8-9], specific theoretical deduction equation as follows:

(1) Continuity equation
Continuity equation of air phase:
\[ \frac{\partial}{\partial t} \left( \alpha_g \rho_g \right) + \nabla \cdot \left( \alpha_g \rho_g \vec{v}_g \right) = \sum_{s=1}^{n} \dot{m}_{gs} \]

(2) Continuity equation of powder particle:
\[ \frac{\partial}{\partial t} \left( \alpha_s \rho_s \right) + \nabla \cdot \left( \alpha_s \rho_s \vec{v}_s \right) = \sum_{i=1}^{n} \dot{m}_{is} \]

Wherein: \( \alpha_g, \alpha_s \) - Air phase, powder particle phase volume distribution percentage; \( \rho_g, \rho_s \) - the density of air phase and the powdery particle phase; \( \vec{v}_g, \vec{v}_s \) - Air phase, and power particle phase velocity; \( \dot{m}_{gs}, \dot{m}_{is} \) - Mass transfer enthalpy of air phase and powder particle phase(\( m_{gs}-m_{gs} \)).

(2) Momentum conservation equation
The momentum equation of the air phase:
\[ \frac{\partial}{\partial t} \left( \alpha_g \rho_g \vec{v}_g \right) + \nabla \cdot \left( \alpha_g \rho_g \vec{v}_g \vec{v}_g \right) = -\alpha_g \nabla p + \nabla \cdot \tau_g + \sum_{s=1}^{n} \left( \vec{R}_{gs} + \dot{m}_{gs} \vec{v}_g \right) + \alpha_s \rho_s \left( \vec{F}_g + \vec{F}_{lif,g} + \vec{F}_{VN,g} \right) \]

Wherein, \( \tau_g \) - Strain tensor of air phase.
\[ \tau_g = \alpha_g \mu_g \left( \nabla \vec{v}_g + \nabla \vec{v}_g^T \right) + \alpha_g \left( \lambda_g - \frac{2}{3} \mu_g \right) \nabla \cdot \vec{v}_g \bar{I} \]

(4) The momentum equation of powder particle phase:
\[ \frac{\partial}{\partial t} \left( \alpha_s \rho_s \vec{v}_s \right) + \nabla \cdot \left( \alpha_s \rho_s \vec{v}_s \vec{v}_s \right) = -\alpha_s \nabla p + \nabla \cdot \tau_s + \sum_{i=1}^{n} \left( \vec{R}_{is} + \dot{m}_{is} \vec{v}_s \right) + \alpha_s \rho_s \left( \vec{F}_s + \vec{F}_{lif,s} + \vec{F}_{VN,s} \right) \]

Wherein, \( \tau_s \) - Strain tensor of powder particle Phase.
\[ \tau_s = \alpha_s \mu_s \left( \nabla \vec{v}_s + \nabla \vec{v}_s^T \right) + \alpha_s \left( \lambda_s - \frac{2}{3} \mu_s \right) \nabla \cdot \vec{v}_s \bar{I} \]

(6) Wherein: \( \mu_g, \lambda_g \) - The molecular viscosity and the bulk viscosity of the air phase, \( \mu_s, \lambda_s \) - The molecular viscosities and bulk viscosities of the powdery particles; \( \vec{F}_g \) - The volume force of the air phase, \( \vec{F}_s \) - The Volume Force of Powder Particle Phase; \( \vec{F}_{lif,g} \) - The lift of the air phase, \( \vec{F}_{lif,s} \) - The lift of particle phase; \( \vec{F}_{mg} \) - The virtual mass force of the air phase, \( \vec{F}_{mS} \) - The Virtual Mass Force of Particle Phase; \( \vec{R}_g, \vec{R}_s \) - Interphase interaction forces, which were closed to each other (\( \vec{R}_{gs} = -\vec{R}_{sg} \)); \( p \) - Two-phases sharing of pressure; \( \bar{I} \) - Unit tensor.

(3) Energy conservation equation
The energy conservation equation of air phase:

$$\frac{3}{2} \frac{\partial}{\partial t} \left( \rho_s T_s + \nabla \left( \rho_s \alpha_s \nu T_s \right) \right) = \left( -p_s \vec{I} + \vec{e} \right) \cdot \nabla + \nabla \cdot \left( k_{Ts} \nabla T_s \right) - \gamma T_s + E_{gs} \quad (7)$$

Energy conservation equation of powder particle:

$$\frac{3}{2} \frac{\partial}{\partial t} \left( \rho_s T_s + \nabla \left( \rho_s \alpha_s \nu T_s \right) \right) = \left( -p_s \vec{I} + \vec{e} \right) \cdot \nabla + \nabla \cdot \left( k_{Ts} \nabla T_s \right) - \gamma T_s + E_{sg} \quad (8)$$

Wherein: $T_s$, $T_g$ - temperature of air phase and the particle; $k_{Ts}$, $k_{Ts}$ - Air phase, powder particle phase diffusion coefficient; $\gamma$- Energy dissipation coefficient of the collision; $E_{gs}$, $E_{sg}$ - Energy exchange between two phases($E_{gs} = E_{sg}$).

2.2. Physical Model

According to the specific nature of the agitation, the physical model of ceramic dry granulation process can be divided into two regions. An area was divided into a moving area by a reamer, blade and its vicinity. The remaining regions were divided into static regions. The entire granulation process was in a closed area. The granulation chamber wall was set as a wall. The walls of the reamers and blades were also set as walls. The intersection of the active and static regions was set as the interface.

Specific physical model and boundary conditions are shown in figure 1.

![Figure 1. Simplified diagram of physical model and boundary conditions.](image)

3. Simulation results and analysis

Analysis figure 2 granulation chamber sectional view of the axial temperature field: when granulation time $t_1 = 4$ min, the maximum temperature inside the granulation chamber was about $70 \degree C$, the minimum value was about $20 \degree C$, the area temperature near reamers, leaves was significantly higher, but powder particle distribution area temperature in the whole granulation chamber was relatively uniform; when granulation time $t_1 = 5$ min, the maximum temperature inside the granulation chamber was about $85 \degree C$, the minimum value was about $20 \degree C$, the area near the reamer and blade’s temperature was significantly higher, the temperature of power particles distribution area in granulation chamber was relatively uniform. There had a small number of regional temperature was too high; when granulation time $t_1 = 6$ min, the maximum temperature inside the granulation chamber was about $95 \degree C$, the minimum value was about $20 \degree C$, the area near the reamer and blade’s temperature was significantly higher, the temperature distribution of the powder granules in the whole granulation chamber showed a great difference. There had some areas’ temperature was too high.
4. Experimental results and analysis

Adopted YTN-1001-type powder comprehensive properties tester measured billet particles’ angle of repose, compression ratio, uniformity, plate angle, analyzed the fluidity of billet particles. From the experimental values showed in table 1 different granulation time of the billet particles fluidity index: when granulation time was 4min, the angle of repose was 49.51°, the compression ratio was 21.47%, uniformity was 18.69, plate angle was 54.68°; when granulation time was 5min, the angle of repose of the billet particles was 29.64°, compression ratio was 9.29%, uniformity was 6.92, plate angle was 31.76°, the fluidity evaluation index of the billet particles was 89.7; when granulation time was 6min, the angle of repose of the particles was 30.58°, compression ratio was 12.68%, uniformity was 8.32, plate angle was 32.11°, particle fluidity evaluation index was 81.6.

Table 1. Ceramic body particles liquidity index of different granulating time.

| Experiment numbers | Granulating time /min | Angle of repose /° | Compressibility /% | Uniformity | Angle of plate /° | Liquidity index |
|--------------------|-----------------------|--------------------|--------------------|------------|------------------|----------------|
| 1                   | 4                     | 45.27              | 20.54              | 17.72      | 52.57            | 56.4           |
| 2                   | 5                     | 26.53              | 9.52               | 6.49       | 32.06            | 89.7           |
| 3                   | 6                     | 29.32              | 11.13              | 7.87       | 30.11            | 81.6           |

5. Conclusion

1. Numerical simulation and experimental results showed that: when granulation time was 5min, the maximum temperature inside the granulation chamber was about 85℃, the minimum value was about 20℃, the region near the reamer and blade’s temperature was relatively high, there are small number of regional temperature was too high, but temperature was relatively uniform of particle distribution area in granulation chamber. The fluidity index of the billet particles was 89.7 at this time, the effective billet particles were 90.66%, which was the optimum value of the billet particles, when the temperature was more than 85℃, the fluidity of the billet particles and the number of effective particles was reduced.

2. The author combines Euler's two-fluid theory, the mathematical model of temperature field in dry milling process was established, which provided the theoretical support for the study of granulation chamber temperature field in dry granulation process and provided a theoretical basis to promote dry milling technology in the building ceramic industry.

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