Fluent simulation of centrifugal atomization of multi-solid wastes molten slag melted by blast furnace slag, fly ash and waste incineration ash

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Abstract. Based on finite element numerical simulation method, Fluent software was used to simulate the centrifugal atomization process of multi-solid wastes molten slag melted by blast furnace slag, fly ash and waste incineration ash. The feasibility of the finite element model in simulating centrifugal atomization was verified by comparing the experimental results with the calculated results. The influence of rotating speed, nozzle angle and the inlet velocity of compressed air injected on the slag particle distribution were studied. Results showed that the rotating speed of the turntable should not exceed 1000 rpm, the inlet velocity of compressed air should be about 5 m/s, and the nozzle angle of compressed air should be set between 40 and 60 degrees, which have positive effect on the centrifugal atomization of multi-solid wastes molten slag. The heat recovery efficiency can reach 73.7% under the condition of 800 rpm rotary speed, 5 m/s compressed air inlet velocity, 0.1 m/s flow rate of 1800 K molten slag beam and in 300 K ambient temperature.

1. Introduction
As the harmful solid by-products of urban industry and life, blast furnace slag, fly ash and waste incineration ash are considered as the resources to prepare CaO-MgO-Al\textsubscript{2}O\textsubscript{3}-SiO\textsubscript{2} glass ceramic since their main compositions are CaO, MgO, Al\textsubscript{2}O\textsubscript{3} and SiO\textsubscript{2}. Also the few amount of Cr\textsuperscript{3+}, Cu\textsuperscript{2+}, Zn\textsuperscript{2+} heavy metal elements in fly ash and waste incineration ash can be utilized as the nucleating agents for glass ceramic\textsuperscript{[1]}. Based on the complementary compositions of different kind of solid wastes, preparation of glass ceramic by multi-solid wastes was more promising compared with preparation by single solid waste\textsuperscript{[2]}.

Rotary cup method is a kind of dry granulation technology, which emphasize for its low energy consumption, unique particle size, controlled morphology and cleanliness\textsuperscript{[3,4,5]}. Preparation of basic glass granule of the fused blast furnace molten slag, fly ash and waste incineration ash through rotary cup method has very important practical significance. Which can make full use of the huge amount heat of molten slag and shorten the procedure of preparation of glass ceramic. At present, the rotary cup method has not been applied in China, and the related research was mainly focused on the laboratory stage or analog simulation. Liu and Yang et al. discussed the influence of different factors on the atomization effect through experiments\textsuperscript{[6,7]}. Yanyan Chen used VOF two-phase flow model for the simulating melt atomization process and verified model accuracy\textsuperscript{[8]}. Fluent contains rich and advanced physical models, including turbulence model, noise model, chemical reaction model and multiphase flow model, which are widely used in the calculation of various fluid models in industry. In this paper, turbulence model and multiphase model in Fluent
software were applied to calculating the centrifugal atomization process of molten slag melted by blast furnace slag, fly ash and waste incineration ash. The influence of rotating speed, nozzle angles of compressed air and the amount of compressed air injected on the slag particle distribution was revealed, which can provide guidance for the optimization scheme of centrifugal atomizing system of multi-solid wastes molten slag.

2. Slag properties parameters and finite element model

2.1 Slag properties parameters

The chemical composition of studied slag is complex and the physical parameters vary greatly with the composition. Therefore, a basic slag system should be selected to simulate the centrifugal atomization effect of the actual slag system on the turntable. By analyzing the chemical components of the solid wastes, it is concluded that the chemical components of the multi-solid wastes are mainly the oxides of Ca, Si, Mg, Al, Fe, Ti and CaF₂. The CaO-MgO-SiO₂-Al₂O₃-CaF₂-Fe₂O₃-TiO₂ basic slag system was selected as the research object. Its components is shown in Table 1. The nucleants in table 1 are mainly the oxides of Cr, Cu, Pd and Zn et al.

| composition | CaO | MgO | SiO₂ | Al₂O₃ | CaF₂ | Fe₂O₃ | TiO₂ | Nucleants |
|-------------|-----|-----|------|-------|------|-------|------|-----------|
| mass (wt %) | 26  | 10  | 30   | 11    | 12   | 4     | 3    | 4         |
| fraction (wt %) |     |     |      |       |      |       |      |           |

The density of testing slag is 2800 kg/m³ which was determined by MH-220s solid-liquid dual-use density tester. RTW-10 melt physical property tester was used to determine the viscosity curve with temperature of the basic slag molten, which is shown in Fig.1. The testing temperature of melted multi-solid wastes was setting at 1500 degrees.

![Fig.1 Viscosity curve with temperature of multi-solid wastes molten slag](image)

2.2 Finite element model

The working principle of centrifugal atomization system is as follows: the melt that flows out of the melting device is in contact with the high-speed turntable under the action of gravity. Under the action of centrifugal force, the melt gradually expands on the surface of the rotating turntable, forming a liquid membrane. When the melt reaches the edge of the turntable, it will be thrown out and atomized into droplets, as shown in Fig.2.
The material of the turntable is 304 stainless steel with a thickness of 30 mm and a diameter of 400 mm. The physical parameters of the material are: density 8010 kg/m\(^3\); Young's modulus 199 GPa; Poisson's ratio of 0.28. After the geometric model was established, it was meshed by ICEM software. Due to the rule of model structure comparison, hexahedron structured grid is adopted. The number of grids in each region is moderate, and the grid encryption is carried out at the turntable wall to improve the calculation accuracy. The grid model is shown in Fig.3.

The grid model was imported into Fluent software to simulate the centrifugal atomization process of molten slag. In the calculation process, the influences of rotating speed, measuring blowing angle of compressed air and measuring blowing gas volume on the distribution of slag particles are mainly considered. VOF dual-phase flow model was applied to simulate the centrifugal atomization process since there were kinds of incompatible fluid component, which were melt and air respectively. In VOF model, different fluid components share one set of momentum equation. Volume efficient ratio of each fluid component were recorded in the calculation. Volume fraction equation was done by solving a set of continuity equations of volume ratios or multiphase ratios. For the q phase:

\[
\frac{\partial \alpha_q}{\partial t} + \mathbf{v} \cdot \nabla \alpha_q = \frac{S_{\alpha q}}{P_q}
\]

(1)

Where \( S_{\alpha q} \) was the source term of mass. The calculation of volume fraction of the principal phase was based on the following constraints:
\[ \sum_{q=1}^{n} \alpha_q = 1 \]  

(2)

The momentum equation was obtained by solving a single momentum equation in the entire region, and the velocity field was shared by other phases. The equation was as follows:

\[
\frac{\partial}{\partial t} \left( \rho \vec{v} \right) + \nabla \cdot \left( \rho \vec{v} \vec{v} \right) = -\nabla p + \left[ \mu \left( \nabla \vec{v} + \nabla \vec{v}^T \right) \right] + \rho \vec{g} + \vec{F} \]  

(3)

Other settings of various solution parameters in Fluent software were as follows:

(1) pressure based solver, 3D model, unsteady state;
(2) turbulence model (Standard k-\(\varepsilon\) model);
(3) the inlet boundary condition was set as the velocity inlet boundary, and the turntable was set as the dynamic wall surface;
(4) SIMPLE algorithm was adopted for pressure-velocity coupling;
(5) Second Order Upwind.

3. Simulation results and analysis

After the completion of the solution in Fluent software, the results were processed in the post-processor. The diagram of the entire flow process is shown in the Fig.4, which shows the phase state diagram of centrifugal atomization of slag at different times. When the melt comes into contact with the turntable, it spreads out on the surface of the turntable. Under the action of centrifugal force, the melt gradually diffuses into a layer of film. After disengaging from the turntable, it forms scattered droplets, and finally forms particles after cooling in the air.

![Contours of Volume fraction (air)](image)

Fig.4 Diagram of centrifugal atomization process of slag on the turntable

As shown in the Fig.5, due to the high viscosity of slag, the viscous force makes the revolving speed of slag accelerate continuously on the turntable and reach the maximum speed at the edge of the turntable.

When the rotary speed is 800 rpm, the molten slag spreads into a thin film immediately after contacting the surface of the turntable. And the thin film turns into lamellar structure, linear shape and dispersed droplet state respectively when it spreads from the heart to the edge of turntable, as shown in Fig.6. This is consistent with the experimental results of centrifugal atomization of slag carried out by Hadi Purwanto et al. in 2005[9].
When the rotating speed of the turntable increasing to 1000 rpm, the slag will not form a lamellar structure near the turntable. After disengaging from the turntable, scattered droplets will be formed directly, as shown in Fig. 7. This is because the rotating speed of the turntable is too fast, and the cohesive force of the slag is not enough to provide centripetal force, so that the slag can't accelerate well with the turntable. Therefore, the speed of the turntable should not be too fast, otherwise it will have adverse effects on centrifugal atomization.
Fig. 7 Slag phase diagram on cross section of the turntable at high speed

For further analysis of rotary granulating process, it is necessary to establish the model of the influence of heat concentrated area, compressed air volume and nozzle angle on the distribution of particles. The participation of compressed air in the process of centrifugal atomization is aiming to increase the cooling rate of molten granules forming on the edge of turntable, which can make full recovery of the huge quantity heat in the molten slag and obtain high quality glass phase granules at the same time. When no compressed air is added, the slag will be scattered under the action of gravity after leaving the turntable, as shown in Fig. 8.

Fig. 8 Slag dispersion form

In order to make enough compressed air participate the heat exchange process, the inlet velocity of compressed air should not to be too small, which was set at 4 m/s at the beginning. The nozzle angle was set within 20 to 80 degrees to observe the effect of nozzle angle on centrifugal atomization. The result is shown in Fig. 9, when the nozzle angle is small, such as 20 degrees, the horizontal blow force makes the slag appear linear, which prevents the slag forming particles. When the nozzle angle is 40 degrees or 60 degrees, the slag keeps a good granular state in the air. When the nozzle angle is bigger, such as 80 degrees, it will also destroy the droplets form. The slag leaving the turntable will be
subjected to a large vertical blowing force, which will present an upward angular shape. The scattered particles will be concentrated and the granulation effect will be weakened.

![Contour plots of Volume fraction (slag) for different nozzle angles](image)

Fig. 9 Influence of different nozzle angles on centrifugal atomization effect

According to the above analysis, the nozzle angle was set to 50 degrees, the inlet velocity of compressed air increased. When the inlet velocity was increased to 5 m/s, the particle morphology of the slag remains intact and there is more compressed air participate the cooling process of the slag. But when the inlet velocity increased to 6 m/s, the slag particles fly up and around and the melt beam was tilted, which had adverse effect on the centrifugal atomization process, as shown in Fig. 10. Therefore, the inlet velocity of compressed air should not be too large, which in this case should be set about 5 m/s.
Also the heat recovery efficiency was simulated and calculated. Based on the above calculation results, we set the condition of heat exchange between molten slag and compressed air as 800 rpm rotary speed, 5 m/s compressed air inlet velocity, 0.1 m/s flow rate of 1800 K molten slag beam and 300 K ambient temperature. The distribution of temperature in the process of centrifugal atomization is shown as Fig.11. After sufficient heat exchange, the heat recovery efficiency can reach 73.7%.

4. Conclusion
By simulating the centrifugal atomization of multi-solid wastes molten slag melted by blast furnace slag, fly ash and waste incineration ash, some meaningful results are obtained, including:

- The centrifugal atomization effect of slag increases with the increase of rotating speed, but it cannot exceed 1000 rpm, otherwise it will have adverse effect on the centrifugal atomization.
- The compressed air nozzle was arranged at the bottom of the turntable to positively influence the centrifugal atomization process of molten slag.
- The inlet velocity of compressed air and nozzle angle have influence on centrifugal atomization, the inlet speed remains about 5 m/s, and the nozzle angle is set between 40 and 60 degrees, which have positive effect on the centrifugal atomization of multi-solid wastes molten slag.
- The heat recovery efficiency can reach 73.7% under the condition of 800 rpm rotary speed, 5 m/s compressed air inlet velocity, 0.1 m/s flow rate of 1800 K molten slag beam and in 300 K ambient temperature.

Acknowledgement
This study was supported by the technology for civil welfare project of Ningbo, China, Nos. 2015C50058.

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