Study of Gas-solid-solid Three-phase Flow in Non-Powered Separator

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Authors’ contributions

This work was carried out in collaboration among all authors. Author WH designed the study, performed the statistical analysis, wrote the protocol and wrote the first draft of the manuscript. Authors JS and JY managed the analyses of the study. Author JM managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

The non-powered separator is one of the key equipment in the dry sand production line, which is responsible for the separation of coarse and fine materials. In this paper, based on the turbulence Standard k – e Model, the air sand powder three-phase fluid model is simplified to gas-solid-solid three-phase flow, and the 3D model of the non-powered separator was built. The process of sand powder separation was simulated by using Fluent software. It is found that the larger the air volume control valve blade angle is, the more sand is removed, and the blade angle can be adjusted in the range of 15° to 60° according to the actual needs in industrial production.

Keywords: Three-phase flow; gas-solid-solid; separator; hydrodynamics; fluent.

1. INTRODUCTION

Concrete is the most basic and widely used building material in the construction industry. With the good momentum of economic development and the rapid development of related industries, the demand for concrete is also increasing year by year. The concrete

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production process can be divided into three stages: raw meal preparation, clinker calcination, and cement grinding [1]. The classification of materials is mainly in the stage of cement grinding.

Many studies showed that the particle size distribution of sand is closely related to the strength of concrete [2]. Therefore, the material classification of concrete is one of the important links in the production process. The sand powder separation equipment in the sand production line mainly includes a vibrating screen and powder separator. The vibrating screen is mainly used in large construction sites and production lines, while the powder separator is mainly used in small batch production. At present, most of the separators in industrial production are centrifugal separators, which mainly use the separation theory of rotating gas-solid two-phase flow, and take into account the separation principle of gravity sedimentation and inertia force in the design, so that the solid particles with different particle size and density suspended in the airflow are subject to different forces, and the coarse particles and powder are separated [3,4].

However, the research of non-powered separator in China is less, mainly relying on experience, lack of theoretical basis. The study of the separation law is not only beneficial to improve the separation effect and concrete quality, but also greatly improve the work efficiency, reduce the workers’ on-site debugging time, which is conducive to the health of workers, and also provides a theoretical basis for the further structure optimization and automation of non-powered separator.

2. MODELING

2.1 Modeling of the Non-powered separator

The main body of the non-powered separator is welded by iron sheets. It is mainly composed of body, two air volume control valves on the left side, a feeding port at the top, a powder outlet at the upper right side, and a sand outlet at the lower end. Its main function is to separate sand and powder from cement concrete materials and produce materials required for subsequent processes after separation. After the material enters from the feeding port at the top, under the action of gravity and the negative pressure of the powder outlet, it separates in the body and leaves from the powder outlet at the upper right end and the sand outlet at the lower end. Among them, most of the sand mainly leaves from the sand outlet and are sent to the corresponding location by belt conveyor for storage. Most of the powder is sucked away by the press connected to the powder outlet and enters the belt powder collector with the airflow. In the inner settling chamber of the powder collector, the coarse powder particles are collected by their gravity sedimentation and fall into the ash hopper, which is sent to the next process for recovery through the screw conveyor at the lower part of the ash hopper. The fine dust particles are discharged into the atmosphere after being collected through the bag with the air, and the particulate matter emission reaches the national emission standard of 30mg/m [3,5,6]. The three-dimensional model of non-powered separator was built by Solidworks, and was imported into Fluent for simulation. To save the time of modeling and simulation and ensure the successful completion of the simulation, the model of the non-powered separator was simplified. The 3D model of the non-powered separator is shown in Fig. 1.

2.2 Modeling of Air Volume Control Valve

The air volume control valve is one of the main air inlets of the non-powered separator, which is composed of four blades with rotating shafts. The opening and closing angle of the valve blade ranges from 0° to 90°. In this study, six angles of 15°, 30°, 45°, 60°, 75°, and 90° were selected as the test objects. The 3D model of the air volume control valve is shown in Fig. 2.

3. AIR-SAND-POWDER FLOW FIELD ANALYSIS MODEL

3.1 Turbulence Model

The state of fluid flow in nature mainly includes laminar flow and turbulent flow. Laminar flow means that there is no mixing between two layers in the flow process, while turbulence means that the fluid is not in the stratified flow state [7]. In the numerical simulation, laminar flow and turbulent flow can be distinguished according to Reynolds number:

\[
Re = \frac{\nu L}{\mu}
\]  

(3-1)

Where \( \rho \) is the fluid density, \( \nu \) is the fluid velocity, \( \mu \) is the fluid viscosity coefficient, and \( L \) is the characteristic length (equivalent to the diameter of a circular pipe).
In practical application, the critical value of the Reynolds number \( Re \) is usually 2300. When \( Re \leq 2300 \), the flow is laminar. When \( Re > 2300 \), the flow is turbulent [8,9]. The turbulence model is used in this study.

\[

\n
G_{k,1} \text{ is the turbulent kinetic energy generation term:}
\]

\[

G_{k,1} = \mu_{e} \frac{\partial u_{i}}{\partial x_{i}} \left[ \frac{\partial u_{j}}{\partial x_{j}} + \frac{\partial u_{j}}{\partial x_{i}} \right] - \frac{2}{3} \omega \cdot \omega \left( \frac{\mu_{e}}{\rho_{i}} \right)
\]

\[

u_{1} + \rho_{i} k_{1}
\]

(3-4)

\[

\mu_{11} = C_{\mu} \left( \rho_{i} k_{1}^{2} / \varepsilon_{1} \right)
\]

(3-5)

Where, \( \mu_{11} \) is the turbulent viscosity of the solid phase, \( C_{\mu} \) can be taken as 0.09.

4. EXPERIMENTAL AND ANALYSIS

4.1 Experimental

The non-powered separator model was imported into the finite element analysis software Fluent, and the Euler model of gas-solid-solid three-phase flow was established, to simulate the sand powder separation rate of the non-powered separator. Using the Fluent analysis module of the ANSYS Workbench platform, the 3D solid model meshed with a total of 6 areas, 50608 nodes, and 30782 units as shown in Fig. 3.

3.2 Standard \( k - e \) Model

According to the complexity of the simulation, turbulence models can be divided into three categories: direct simulation (DNS), Reynolds time average (RANS), and large eddy simulation (LES) [10,11]. RANS model is widely used in engineering because of its economical calculation and reasonable accuracy. RANS turbulence model includes standard \( k - e \) model and its various modified schemes as well as Reynolds stress model (RSM) [12].

The standard \( k - e \) model is a two-equation turbulence model proposed by Lauder and Spalding [13,14]:

\[

\n
\n
(3-2)

\[

\n
Where, \( S_{k,1} \) and \( S_{e,1} \) are the effect of air turbulence term.

4.1.1 Mathematical method

The three-phase flow model is the Euler model. When air, sand, and powder pass through the flow field, the flow rate of each phase is proportional to the total flow rate of the whole flow field, which is called phase volume fraction \( \alpha_{q} \) [15], where \( \alpha_{1} \) is the air phase, \( \alpha_{2} \) is sandstone facies, \( \alpha_{3} \) represents powder phase. The volume fraction represents the space occupied by each phase, and the air phase, sand phase, and powder phase conform to the conservation of mass and momentum.
The volume of phase \( V_q \) is:

\[
V_q = \int \alpha_q dV 
\]  
(4-1)

Then the volume of air phase, sand phase, and powder phase is:

\[
V_1 = \int \alpha_1 dV 
\]  
(4-2)

\[
V_2 = \int \alpha_2 dV 
\]  
(4-3)

\[
V_3 = \int \alpha_3 dV 
\]  
(4-4)

Where \( \sum_{q=1}^{n} \alpha_q = 1 \), and \( \alpha_1 + \alpha_2 + \alpha_3 = 1 \).

The air volume fraction is 0.1, the sand volume fraction is 0.6, and the powder volume fraction is 0.3.

### 4.1.2 Calculation conditions

In the dynamic simulation process, the granular material was defined as sand and powder, the density was 1600kg/m\(^3\) and 1400kg/m\(^3\) respectively, the particle size diameter was 0.000178m and 0.000015m respectively, and the viscosity was 0.00001. In the numerical simulation, the finite volume method was used to discretize the equations, and the pressure field was obtained by solving the model. The gas boundary conditions were set as follows: the sand inlet and air inlet are velocity inlet, the material falling velocity at the sand inlet was 1m/s, the hydraulic diameter at the sand inlet was 1.13m, and the hydraulic diameter at the air inlet was 1.7m; the sand outlet and powder outlet are pressure outlet, and the pressure at the sand outlet was 0Pa, the hydraulic diameter was 0.72m, because the powder outlet was connected with the air ejector fan, the pressure was selected according to the parameters of the air ejector fan. In this study, -1500 Pa was selected, and the hydraulic diameter was 1.7m. The wall surface adopted non-slip boundary.

### 4.2 Results and Discussion

When the included angles of air volume control valve blades were 15°, 30°, 45°, 60°, 75°, and 90° respectively, the flow field was analyzed respectively. The simulation calculation time was 10s, the time step was 0.01, and the time step was 1000. After 10s, the operation of the non-powered separator basically reached a stable state, and the analysis cloud chart of the instantaneous velocity flow field of sand movement in the axial cross-section is shown in Fig. 4.

It can be seen from Fig. 4 that when the blade angle of the air volume control valve changes from 15° to 90°, the sand velocity at the sand outlet decreases gradually. On the contrary, the sand velocity at the powder outlet increases gradually.

The solver was set in Fluent to calculate the mass of sand passing through the two outlets at different angles, as shown in Table 1 and Fig. 5.

It can be seen from Table 1 and Fig. 5 that when the valve blade angle increases gradually, the sand mass at the sand outlet of the non-powered separator decreases gradually, while at the powder outlet, it increases gradually.

Similarly, the powder mass passing through the two outlets per second at different angles was calculated, as shown in Table 2 and Fig. 6.

It can be seen from Table 2 and Fig. 6 that when the valve blade angle increases gradually, the powder mass of the sand outlet and the powder outlet of the separator changes regularly, in which 30° is the extreme value of the powder mass at the sand outlet, and 45° is the extreme value of the powder mass at the powder outlet.

| Angle(°) | 15 | 30 | 45 | 60 | 75 | 90 |
| --- | --- | --- | --- | --- | --- | --- |
| Sand Outlet(kg/s) | 997.9 | 949.11 | 920.55 | 898.26 | 890.4 | 872.79 |
| Powder Outlet(kg/s) | 309.19 | 365.37 | 392.57 | 416.8 | 435.85 | 440.61 |

| Angle(°) | 15 | 30 | 45 | 60 | 75 | 90 |
| --- | --- | --- | --- | --- | --- | --- |
| Sand Outlet(kg/s) | 359.25 | 310.71 | 360.06 | 370.76 | 322.92 | 300.57 |
| Powder Outlet(kg/s) | 245.5 | 242.42 | 195.14 | 209.96 | 251.8 | 275.5 |
Fig. 4. Flow field analysis cloud images at different angles
Finally, the powder content at the outlet of sand and the sand content at the outlet of powder are calculated at different angles:

\[
\text{Powder content of sand outlet} = \frac{\text{Powder mass of sand outlet per unit time}}{\text{Sand mass} + \text{Powder mass}} \tag{4-5}
\]

\[
\text{Sand content of sand outlet} = \frac{\text{Sand mass of powder outlet per unit time}}{\text{Sand mass} + \text{Powder mass}} \tag{4-6}
\]

The results are shown in Table 3.

It can be seen from Table 3 and Fig. 7 that when the angle range is from 15° to 45° the amount of sand at the powder outlet decreases gradually, and the amount of sand at the sand outlet increases gradually. When the angle range is from 45° to 90° the amount of sand at the powder outlet also decreases gradually, but the amount of sand at the sand outlet also decreases gradually.

**Fig. 5. Sand mass change chart**

**Fig. 6. Powder mass change chart**
Table 3. Sand content and powder content at different angles

| Angle(°) | 15   | 30   | 45   | 60   | 75   | 90   |
|----------|------|------|------|------|------|------|
| Powder content of sand outlet | 26.47% | 24.66% | 28.12% | 29.22% | 26.61% | 25.62% |
| Sand content of powder outlet | 55.74% | 60.11% | 66.80% | 66.50% | 63.38% | 61.53% |

Fig. 7. Sand content and powder content

Fitting the data above, polynomial equations can be obtained between the valve blade angle and the sand content and the powder content, respectively:

\[ C_1 = 0.0027a^4 - 0.0397a^3 + 0.1977a^2 - 0.3733a + 0.4774 \ (R^2 = 1) \]  \( (4-7) \)

\[ C_2 = 0.0028a^4 - 0.0383a^3 + 0.1663a^2 - 0.2253a + 0.6515 \ (R^2 = 0.9917) \]  \( (4-8) \)

Where \( C_1 \) is the powder content of sand outlet, \( C_2 \) is the sand content of powder outlet, and \( a \) is the valve blade angle.

5. CONCLUSION

By analyzing the variation of powder content of finished sand at different angles of the air volume control valve, it can be found that the larger the opening of the valve blade angle is, the more sand will be removed away. Considering various influencing factors and costs, the valve blade angle should be adjusted in the range of 15° to 60°.

In addition, when the fan blade angle is 30 degrees, the dust content at the sand outlet and the dust outlet has an extreme value, which can be further discussed in future research.

Due to the different requirements of powder content in industrial applications, the standards required for different production requirements are not the same. Therefore, according to the above rules, the angle of controlling the air volume control valve can be summarized to control the powder content of finished sand, so as to improve the separation effect and improve the work efficiency. The law also provides a theoretical basis for the structure optimization of the non-powered separator and the control of the automatic air volume control valve.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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