Numerical Simulation of the Force Analysis of Gas-Solid Two-Phase Sepiolite Particles in a Horizontal Pipe

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Abstract. In order to study the force that sepiolite particles exert in a horizontal pipe, a method for analysing the simulation of the two-way coupling of gas-solid two-phase flow of sepiolite particles has been proposed in this paper. A three-dimensional model of the gas-solid two-phase flow of sepiolite particles was constructed, based on the Discrete Element Method (EDM). In this model, the force and motion of the sepiolite particles were established according to Newton’s second law, turbulent flow was simulated using the k-ε model, and the two-way coupling correlation between the sepiolite particles and the turbulent flow was established according to Newton’s third law. Through numerical simulation of the gas-solid two-phase flow of sepiolite particles in a horizontal pipe, the distribution of both the velocity and pressure were obtained. In addition, the properties of the gas-solid two-phase flow of sepiolite particles were obtained. The results of the simulation demonstrated that the main forces acting on the sepiolite particles in a horizontal circular pipe in a turbulent state were drag, lift, gravity and the buoyancy of the particles. It was found that the Basset force, the Magnus force, the additional mass force and the pressure gradient force had a negligible influence on the movement of the sepiolite particles.

1. Introduction

Gas-solid two-phase flow is a common phenomenon in multiple industries; analyzing the force acting on the particles is the core problem when studying the motion of particles in gas-solid two-phase flow. Most studies on gas-solid two-phase flow previously focused on single-phase flow, and the majority of them relied on experimental data to obtain the relevant experimental reference data. For example, Kliafas and Holt [1] used Laser Doppler Velocimetry to measure the air-solid two-phase flow in a square sectioned 90° bend and they obtained the mean streamwise and radial velocities. Tsuji et al. [2], published information on the particle velocity and the spatial development of the particle size distribution, obtained from Phase-Doppler Anemometry (PDA). Measurements of particle concentration and particle velocity were performed by Akilli et al. [3] at various locations along a horizontal pipe using a fiber-optic probe.
Due to the complexity of gas-solid two-phase flow, it is difficult to obtain comprehensive information about the entire flow field using the experimental method, and the different means of measurement have their errors and limitations. As a result, more and more attention has been paid to numerical simulation. Two primary methods are generally used at present in order to simulate gas-solid two-phase flow, including the Two-Fluid Model (Euler-Euler model), and the Particle Track Model (Euler-Lagrange model). For example, Lain and Sommerfeld [4] demonstrated three-dimensional numerical computations performed using the Euler-Lagrange approach in connection with the k-ε and a Reynolds Stress turbulence model that accounted for full two-way coupling. For all the forces acting on the particles that were considered, the study proved that the model could accurately predict gas-solid two-phase flow behavior. Kozolub et al. [5] presented a numerical simulation of the flow inside a cyclone separator at high particle load. The gas and gas-particle flows were analyzed using a commercial computation fluid dynamics program. The two-phase gas-solid particles flow was modeled using an Euler-Lagrange approach, which accounted for the two-way coupling between the phases. Zhao et al. [6] simulated gas-solid two-phase flow in pipe with a 90o bend using the Euler-Lagrange method with the commercial CFD computer code FLUENT.

When particles are carried by airflow, they demonstrate complex flow behaviors in a pipe due to the forces acting on them. It is necessary to deeply study the gas-solid two-phase flow law and accurately describe the forces acting on the particles in the flow field. The motion of sepiolite particles in a pipe results from the interactions between several forces, including gravity, drag, buoyancy, virtual mass force, the pressure gradient force, the Basset force, the Magnus force, and the Saffman force. In many simulations, the particle motion can be simplified based on Maxey and Riley's formula, but the jury is still out on the trade-offs of the choice of forces. For example, Pan and Banerjee [7] considered drag, the pressure gradient, and gravity; Dorgan and Loth [8] considered drag and gravity; Vance et al. [9] only considered drag; The numerical simulation in Chen et al. [10] considered drag, lift, Brownian force and gravity. Hojjat [11] studied the effects of particle collisions and gas-solid bidirectional coupling on turbulent fluctuations in the channel. Only the drag and lift of the fluid acting on the particles were considered in the numerical simulation. In general, most researchers considered drag and gravity, and quite a few considered the buoyancy exerted on the particles, while the pressure gradient force, the Basset force and the virtual mass force were usually ignored. However, Elghobashi and Truesdell pointed out that the Basset force is the most important force in the direction opposite to gravity.

In summary, there are differences in the physicochemical and mechanical properties of different kinds of particles, and the analysis of the forces of different kinds of particles in the simulation of gas-solid two-phase flow has been presented by many different researchers. The flow of sepiolite particles in gas-solid two-phase flow based on the COMSOL software platform, has been simulated in this paper. According to the characteristics of sepiolite, a non-metallic mineral powder, a transient analysis of sepiolite particles in horizontal tubes was carried out. This analysis has provided the basis for the selection of the forces acting on sepiolite particles in the simulation of gas-solid two-phase flow.

2. Materials and Methods

2.1. Force analysis of sepiolite particles

Sepiolite belongs to the structural family of 2:1 phyllosilicate, which is a hydrous magnesium silicate [12]. It exhibits microfibrous morphology and has a wide range of particle sizes. Airflow crash was adopted to deal with the materials, after that, the distribution of the grain size was 1μm to 100μm which was then divided into ultrafine powder, fine powder, medium powder, and coarse powder. The physical properties of the sepiolite powder were then tested by using the volume method, the direct shear method and other methods, as shown in Table 1.
### Table 1. Physical properties and particle size classification of the sepiolite powder.

| Characteristics of the sepiolite powder | Magnitude of force |
|----------------------------------------|--------------------|
| Average particle size/μm               |                    |
| Ultrafine powder:1                     |                    |
| Fine powder:5(2~10)                    |                    |
| Medium powder:38(10~50)                |                    |
| Coarse powder:62(>50)                  |                    |
| Density/ (g · cm⁻³)                    | 1.328              |
| Motion viscosity/ (m² · s⁻¹)           | 401.77 × 10⁻⁶      |
| Dynamic viscosity/ (Pa · s)            | 0.7593             |

According to the results of the scholars' research above of the force analysis of the particles, it is known that the motion of particles is due to the resultant force of the airflow through the traction force, the Saffman lift force and so on, overcomes the resultant force due to gravity, as well as the friction force, the adhesion force and other forces that hinder the movement of the particles. The thermophoretic force, electrophoretic force and electrostatic force generated by the thermal motion of ultrafine particles are negligible. In the following sections, gravity, buoyancy, drag, the pressure gradient force, the additional mass force, the Basset force, the Magnus force and the Saffman lift force have mainly been considered. The motion equation of a single particle in its general form is:

\[ ma = m \frac{dv}{dt} = \sum F \]  \hspace{1cm} (1)

Where \( m \) the mass of the particle is, \( ma \) is the inertia of the particle, and \( \sum F \) represents the combined external force acting on the particle.

The following is the force analysis of single particles of sepiolite powder of 62μm, as shown in Figure 1.

![Figure 1. Force analysis diagram of sepiolite particles of 62μm.](image-url)
Drag
When sepiolite particles move relative to the gas fluid phase, a force will be generated to either hinder or push the particles. The expression of the drag on a single spherical particle in the airflow can be written as:

$$F_D = C_D \cdot \rho_g \cdot \frac{|V-V_p|}{2} \cdot \frac{(V-V_p) \cdot \pi d_p^2}{4}$$

(2)

Where, \( V \) is the gas’s velocity, \( V_p \) is the particle’s velocity, \( \rho_g \) is the air density, \( d_p \) is the particle’s diameter, \( C_D \) is the drag coefficient, the value of which is 0.44.

Buoyancy
As the sepiolite particles are either in or carried by a fluid, the effect of buoyancy always acts on the particles, which can be written as:

$$F_B = \rho \cdot V_p \cdot g = \frac{1}{6} \pi \cdot d_p^3 \cdot \rho_g \cdot g$$

(3)

Gravity
The force produced by the acceleration due to gravity. The force acting on a particle moving in a fluid is minus the buoyancy force on the particle in the fluid.

$$F_g = m_p g \left( \frac{\rho_p - \rho}{\rho_p} \right)$$

(4)

Where, \( \rho_p \) is the sepiolite particle’s density.

Pressure gradient force
For spherical particles, the resultant pressure acts on the particles in the opposite direction to the pressure gradient. If the pressure gradient in the direction of the fluid flow is expressed by \( \frac{\partial p}{\partial l} \), the pressure gradient force acting on the spherical particles can be written as:

$$F_p = -\frac{\pi d_p^3}{6} \cdot \frac{\partial p}{\partial l}$$

(5)

Additional mass force
When the sepiolite particles move in a straight line with equal acceleration in an ideal incompressible, inviscid, stationary fluid, the surrounding fluid is driven to accelerate by the sepiolite. The force pushing the surrounding fluid to accelerate at a given acceleration \( a \) is called the additional mass force, which can be written as:

$$F_m = -0.5 \frac{\pi d_p^3}{6} \cdot \rho \cdot a_p$$

(6)

Where, \( a_p \) is the acceleration of the particle.
The Basset force
In a viscous fluid, when sepiolite particles move at an arbitrary variable speed in a straight line in the flow field, there is not only an additional mass force acting on the particles but also increased resistance due to the variable acceleration of the particles in the viscous fluid. This force is defined as the Basset force:

\[ F_{Ba} = \frac{3}{2} \cdot d_p^2 (\pi \rho \mu) \int_{t_0}^{t} (t - t') \frac{1}{2} \frac{d}{dt} (u - u_p) dt \] (7)

Where, \( t_0 \) is the initial time and \( t' \) is the integral’s variable.

The Magnus force
In the process of gas-solid two-phase flow, the asymmetric collision of sepiolite particles will cause the particles to rotate. When a sphere of the sepiolite powder rotates in the flow field, the force perpendicular to the flow direction of the flow field from the upstream side to the downstream side is the Magnus force, which can be written as:

\[ F_m = \frac{1}{8} \pi \cdot \rho \cdot d_p^3 \cdot \omega \cdot (v - v_p) \] (8)

Where, \( \omega \) is the particles’ angular velocity.

Saffman lift force
When the sepiolite particles move in a flow field with a velocity gradient, as the fluid velocity on either side of the sepiolite particles is inconsistent, a lift force from a low flow rate to a high flow rate will be generated in the sepiolite powder particles, which is called the Saffman lift force.

The bidirectional coupling equation between the airflow and sepiolite particles can be obtained from the above partial derivatives of the particles, which can be written as:

\[ F_s = 1.6 d_p^2 \cdot (\rho \mu)^2 (u - u_p) \left| \frac{du}{dy} \right| \] (9)

Then the equation for the motion of the particles can be obtained from Newton’s second law. The momentum exchange between the sepiolite particles and the gas is given as:

\[ m_p \frac{dU_p}{dt} = G + F_D + F_{Saffman} + F_H + F_p + F_m + F_{Ba} + F_M \] (10)

Where \( m_p \) the mass of the sepiolite particles is, \( U_p \) is the velocity of the particles, \( t \) is the time that the particles move for.

The coupling equation between the gas and the particles can be obtained from the partial derivative of the forces acting on the sepiolite:

\[ \frac{\partial F_V}{\partial t} = - \sum_{j=1}^{N} F \cdot \delta \cdot \Delta t \] (11)

Where \( \delta \) is the force factor, \( N \) is the number of forces, \( \Delta t \) is the unit interval of time.
By substituting the sepiolite particles and the continuous phase parameters into the equation of each force model, the relationship of the magnitude of each force model in the characteristic relaxation time can be obtained, as shown in Table 2.

Table 2. The estimated force of the sepiolite particles at the inlet of a channel.

| Type of force         | The magnitude of the force (N) |
|-----------------------|-------------------------------|
| Drag                  | 2.0×10^{-8}                  |
| Saffman lift force    | 8.2×10^{-11}                 |
| Buoyancy              | 3.1×10^{-11}                 |
| Gravity               | 8.6×10^{-12}                 |
| Additional mass force | 9.4×10^{-15}                 |
| Pressure gradient force | 3.1×10^{-14}               |
| Basset force          | 2.3×10^{-13}                 |
| Magnus force          | 9.3×10^{-14}                 |

The sepiolite particles move in the fluid due to the viscosity of the fluid; the motion of the sepiolite particles relative to the fluid creates drag. Therefore, drag is the dominant factor in the movement of sepiolite particles. It can be seen from the magnitude of the forces that:

\[ F_D \geq F_{\text{Saffman}} \geq F_B \geq G \geq F_{\text{fla}} \geq F_M \geq F_p \geq F_a \, . \]

2.2. Numerical simulation of the forces acting on the sepiolite particles

The CFD-DPM model was adopted in this paper, and the two-way coupling N-S equation was adopted in order to solve the gas-phase motion law. The standard k-ε turbulence model was adopted to solve the problem. The motion of the particles was obtained by solving Newton's second law, and the coupling of the gas-solid two-phase was realized using Newton’s third law.

The gas-phase continuity equation can be given as:

\[
\frac{\partial \theta_f}{\partial t} + \nabla \cdot (\theta_f u_f) = 0
\]  \hspace{1cm} (12)

Where \( u_f \) is the gas velocity and \( \theta_f \) is the volume fraction of the gas phase.

The momentum equation of the gas phase is as follows:

\[
\frac{\partial (\theta_f \mu_f)}{\partial t} + \nabla \cdot (\theta_f \mu_f u_f) = -\frac{1}{\rho_f} \nabla P - \frac{1}{\rho_f} F_{\text{fla}} + \theta_f g + \frac{1}{\rho_f} \nabla \cdot \tau
\]  \hspace{1cm} (13)
The equation for the acceleration of the particles can be written as follows:

\[
\frac{du}{dt} = D_p(u_f - u_p) - \frac{1}{\rho_p} \nabla P + g - \frac{1}{\theta_p \rho_p} \nabla \tau_p + F_s
\]

(14)

The characteristics of the particles were mapped to an Euler grid, and the properties of the particle’s phase were also mapped back to the particles by calculating the Euler grid. For example, for particles with a position of \( x_p \), the coordinates of the particle were \((x_p, y_p, z_p)\), the interpolation factor component expression in the x-axis direction can be written as:

\[
S_x^i(x_p) = \begin{cases} 
0 & x_{i-1} \geq x_p \geq x_{i+1} \\
1 & x_p = x_i 
\end{cases}
\]

(15)

The interpolation factor component for the y-axis is similar to the equation for the x-axis; the expression for \( \theta_p \) is mapped back to the grid \( i \) which can be written as:

\[
\theta_p = \frac{1}{\Omega_i} \sum_{n=1}^{N_i} \Omega_p n_p S_{p_i}
\]

(16)

From the law of conservation of volume, it can be obtained that:

\[
\theta_p + \theta_f = 1
\]

(17)

The implicit numerical integral equation of a particle’s velocity can be written as:

\[
u^{n+1}_p = u^n_p + \Delta t \left[ D_p u^{n+1}_{f,p} - \frac{1}{\rho_p} \nabla F_p^{n+1} - \frac{1}{\theta_p \rho_p} \nabla \tau_p^{n+1} + g + F_s \right] / (1 + \Delta t D_p)
\]

(18)

The positions of the particles are updated over time as follows:

\[
x_p^{n+1} = x_p^n + \Delta t u^{n+1}_p
\]

(19)

A geometric model was then established using COMSOL Multiphysics, and the structure and grid model that were created have been shown in Figure 2. The flow field was defined as a horizontal circular pipe with a diameter of 15mm and a length of 150mm. In order to better realize the force analysis of the sepiolite particles in the horizontal pipe according to the actual problems, the geometric model was divided into a suitable grid as shown in Figure 3. From the calculation, the total number of grid elements was 486,489, and the average grid quality was 0.1751.
The Reynolds number $Re$ was used to determine the state of the fluid in the horizontal pipe, however, when determining the relative motion state between the particles and the fluid, the particles’ Reynolds number for a particle size $Re_p$ should also be considered, which can be written as:

$$Re_p = \frac{d_p v \rho}{\mu}$$

(20)

Where, $d_p$ is the diameter of a sepiolite particle, $v$ is the relative velocity of the particles and the fluid, $\rho$ is the density of the fluid and $\mu$ is the viscosity coefficient of the fluid.

Generally, when the Reynolds number $Re \leq 2000$, the flow will be laminar, and when the Reynolds number $Re \geq 4000$, the flow will be turbulent. It has been calculated that when the velocity in a horizontal pipe is less than $2.1m/s$, there will be laminar flow, and when the velocity in a horizontal pipe is greater than $3.7m/s$, there will be turbulent flow. Pneumatic transport of sepiolite powder in a horizontal pipe will result in turbulent flow.

The boundary conditions for the calculation of the particles’ trajectory are:

The gas-phase inlet is the velocity inlet, the inlet velocity is $4m/s$, the outlet is the pressure outlet, and the value of the pressure is $0$; The wall conditions were set as an adiabatic non-slip surface.

The particle phase inlet release mode was set as 50 random releases at a time, with a step length of $0.001$ and 10 releases, all conditions were rebound, and the exit was frozen.
3. Results and Discussion

3.1. Gas pressure and gas velocity distribution

Figure 4 has shown the pressure distribution cloud diagram in a horizontal pipe under the condition of gas-solid flow: the pressure of the gas gradually decreased in the direction of flow due to the action of the resistance along the pipe. It can be seen that the results of the simulation basically conformed to the theoretical pressure distribution in a pipe under turbulent conditions.

![Figure 4. Distribution cloud of the gas pressure in a horizontal pipe.](image)

By observing the distribution of the gas phase velocity in a horizontal pipe, as shown in Figure 5, it can be found that the gas flow rapidly turns into a fully turbulent state after entering the pipe, and its maximum velocity is located at the center of the pipe’s section and slowly decreases in the radial direction.

![Figure 5. Distribution cloud of the gas velocity in a horizontal pipe.](image)

3.2. Simulation results

The kinetic energy and displacement of the sepiolite particles in the z-direction in a horizontal pipe under the different forces have been shown in Figure 6 and Figure 7 respectively.

From Figure 6 it can be seen that, under the condition of considering all the forces, the kinetic energy of the particles displays an upward trend at 0s-0.02s, fluctuates at 0.02s-0.04s, and reached stability after 0.04s. As can be seen from Figure 6 (a), when the Saffman force was not considered, the
curve demonstrated a steady upward trend until it reached equilibrium after 0.04s, and the overall kinetic energy of the particles decreased. It can be seen from Figure 6 (b) that when gravity was not taken into account, the curve was basically fitted to the particles when they received all the forces at 0s-0.02s, and the curve fluctuated at 0.02s-0.04s, and reached a stable value after 0.04s. At this time, the kinetic energy of the particles was lower than that of the particles when they received all the forces. It can be seen from Figure 6 (c) that, when the buoyancy was not taken into account, the kinetic energy curves of the two particles had the same trend. When it reached a stable state at 0.04s, the kinetic energy of the particles was slightly lower than that of the particles under the full forces when the buoyancy was not taken into account. It can be seen from Figure 6 (d) (e) (f) (g) that the two curves were almost completely fitted when the Magnus force, the Basset force, the pressure gradient force and the additional mass force respectively, had not been considered. Therefore, it can be concluded that the influence of the Magnus force, the Basset force, the pressure gradient force and the additional mass force on the kinetic energy of the sepiolite particles in horizontal circular tubes could be ignored. The effects of Saffman lift, gravity and the buoyancy on the movement of the sepiolite particles in a horizontal tube were as follows: \( F_S > F_G > F_B \).

**Figure 6.** Comparison of the kinetic energy of the sepiolite particles under different force conditions
It can be seen from Figure 7 that, under the condition of considering all the forces, the displacement of the particles in the z-direction declined at 0s-0.38s, and remained unchanged after 0.38s. As can be seen from Figure 7 (a), when the Saffman force was not considered, the two curves basically had the same trend. However, when the Saffman force was ignored, particle deposition was more evident. As can be seen from Figure 7 (b), when the effect of gravity was not taken into account, the curve displayed a gradual upward trend, which was completely different from the trend of the curve of the particle displacement in the z-direction under the full force. It can be seen from Figure 7 (c) that, when buoyancy was not taken into account, the displacement curves of the two particles in the z-direction had basically the same trend. It can be seen from Figure 7 (d) (e) (f) (g) that the two curves were basically completely fitted when the Magnus force, the Basset force, the pressure gradient force and the additional mass force, respectively, were not considered. Therefore, it can be concluded that the influence of the Magnus force, the Basset force, the pressure gradient force and the additional mass force on the z-direction displacement of sepiolite particles in horizontal circular tubes can be ignored. The effects of Saffman lift, gravity and lift on the movement of sepiolite particles in a horizontal tube are as follows: $F_G > F_S > F_B$.

**Figure 7.** Comparison of the Z-direction displacement of sepiolite particles under different force conditions
4. Conclusion
In this paper, a numerical simulation of sepiolite particles in a horizontal pipe has been carried out using COMSOL Multiphysics. By calculating the flow state of the sepiolite particles in gas-solid two-phase flow, the following conclusions can be drawn:

The gas-phase pressure gradually decreased in the flow direction of the gas-solid due to the action of the resistance in the pipe, and the maximum velocity of the gas-phase was found to be at the center of the horizontal circular pipe after the flow had been established.

According to the force analysis of single particles, it can be concluded that the main forces acting on the sepiolite particles in a horizontal circular pipe in a turbulent state were drag, lift, gravity and the buoyancy of the particles themselves, while the Basset force, the Magnus force, the additional mass force and the pressure gradient had a negligible influence on the movement of the sepiolite particles.

Among the main forces that were acting on the sepiolite particles in the horizontal pipe, drag was the main force that caused particles to move, lift had the largest influence on the kinetic energy of the sepiolite particles, followed by gravity, and the buoyancy had the smallest influence. Gravity caused the biggest change in the displacement in the Z-direction of sepiolite particles, followed by lift, and the smallest change was caused by the particles’ buoyancy.

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