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Characterization and measurement of apparent viscosity of solid particles in fixed beds under high temperature

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ABSTRACT

In order to intensively understand the interacting forces between solid particles, apparent viscosity was introduced to characterize the resistance of particles against movement. On this basis, a measuring method was developed, through which the torque exerted on a rotating blade inside a solid particle layer was measured. The apparent viscosity was then acquired based on the motion equations of the particles. The influences of various parameters such as type of blade tip, blade position inside the powder layer, particle size/shape, and temperature were discussed and analyzed. The results indicated that at room temperature, the shape of solid particles gives much more important effect on their apparent viscosity; while, under higher temperature, particle size tends to play a major role. The apparent viscosity of iron particles increases with increasing temperature. Good linear relationships between the logarithm of the apparent viscosity of iron particles with 75 μm and the reciprocal of the temperature are observed over different temperature ranges.

1. Introduction

Fluidized bed is well known as an ideal reactor to treat finely sized materials due to better utilization of energy and lower pollutant emissions. However, its widespread commercialization is limited mainly due to particle agglomeration and the subsequent defluidization [1,2]. Many previous researches [3,4] have been performed on the factors affecting sticking, which include temperature, fluidizing velocity, gas atmosphere, material species, as well as particle size and shape. However, the mechanism of particle agglomeration still remains uncertain. Theoretically, it could be roughly considered that defluidization depended on a balance between the cohesive force among particles and the fluid gas drag forces acting on them. Agglomerates formed when the cohesive force (adhering force) was larger than gas drag force (separating force), in this case the probability for defluidization increased. The fluid gas drag force exerted on particles strongly depends on the gas flowing conditions. While the cohesive force, which behaves as the resistance of particles against movement, tends to be determined by the interaction between particles. This is closely related to the intrinsic properties of the constituent particles such as compositions, texture, size and shape. Some researchers [5–7] discussed the probable reasons of cohesion force between metal particles, which include formation of solid/liquid bridges, neck growth, or sintering. However, the data on magnitude of cohesion forces are extremely limited due to the measuring difficulties.

In this study, apparent viscosity of solid particles is introduced to express the ability of particles against movement, which could be reasonably considered as the comprehensive results of interacting forces between particles including external friction and cohesive forces. Further, an experimental measuring method was investigated. In this technique, the torque acted on the rotating blade in solid particle layer was measured, and then the apparent viscosity can be obtained based on the motion equations.

In previous research, solid viscosity has been widely investigated [8–10]. It essentially characterizes the surface softening level of solids. As temperature increases, the solid surface will soften and deform due to enhancement of atom diffusion, the softened material on the surface behaves as a fluid. Fluid-like viscous property tends to appear on the surface, whose magnitude is characterized by solid surface viscosity. Normally, the solid viscosity decreases with increasing temperature [9,10]. Moreover, the decreases of solid viscosity generally indicates an increased adhesion property of particles: the decrease of surface viscosity means that the cohesive forces caused by surface sintering and melting of the particles are increasing, which may lead to particle agglomeration and sticking; while infinite surface viscosity suggests that the solid particles show no adhering ability. The apparent viscosity of particles, proposed in this research, is different with the solid viscosity mentioned above. It characterizes the magnitude of interactions between particles such as bridging and sintering forces, which constitute the main resistance of particles against movement. A larger apparent viscosity indicates larger cohesive forces between particles, as well as stronger adhesion properties.

On the other hand, much work has been conducted on apparent viscosity measurements in a fluidized bed using a paddle impeller [11,12], a cylinder [13,14], or the terminal velocity of a falling sphere [15,16]. The data obtained represents the apparent viscosity of gas/liquid–solid

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suspensions and reflect the ability of the slurry resisting shear deformation. As mentioned above, in fluidized bed two kinds of forces, fluid gas drag force and interaction forces among particles exert on solid particles (the gravity can be negligible especially under high temperature). The apparent viscosity of the above mentioned gas–solid slurry is essentially the combined result of these two kinds of forces. While the data in this research tends to characterize the magnitude of interacting forces among particles and tries to abandon the influence of gas drag force. The measurement of the apparent viscosity of solid particles in this study was carried out under fixed bed situations. It emphasizes the effects of intrinsic particle properties such as compositions, texture, size and shape on their resistance against movement.

2. Experimental

2.1. Apparent viscosity of solid particles and the measuring principle

When the object immersed in the liquid (e.g., probe of the testing equipment) rotates, the rotating object will receive the viscous torque of the fluid. It is thought that mutual attractive force exists among liquid molecules, which is the direct reason for the generation of viscosity in liquid. Liquid viscosity reflects the magnitude of the attractive force among the liquid molecules, as well as the resistance of liquids against movement. The torque exerted on the rotating probe inside liquids has a close relationship with the liquid viscosity, and the traditional rotating test method measures the torque to obtain the viscosity of liquid, based on Newton's law of viscosity.

Similarly, interacting forces between solid particles such as bridging and sintering forces exist between solid particles [6,7], which are also the direct reason for the particles resisting movement. In this research, the ability of particles against movement is characterized by apparent viscosity, which tends to be the comprehensive results of interacting forces between particles.

When the probe rotates in solid particles, the probe will also receive torque from the rotating solid particles. The magnitude of this torque is closely related to the apparent viscosity of the solid particles mentioned above. However, the above testing method for liquid viscosity (based on Newton's law of viscosity) requires a strict non-slip condition between the fluids and probe. That is obviously not suitable for measurement of apparent viscosity of solid particles since the slip condition exists between the particles and the probe (solid particles cannot keep the same flow rate as the standard probe). A measuring method based on energy dissipation principle was applied in this study, and the measuring principle was shown as the follows. Similar measuring method has been used to obtain the apparent viscosity of non-Newtonian fluids such as gas–solid/liquid–solid slurry [17,18], while different researchers designed different shapes of probes for different purposes.

When a blade is rotated inside the powder, it acts as an agitator, and its power number, N_P, is defined as [17]:

$$N_p = \frac{P}{\rho N_r^3 D^5} = \frac{T \cdot (\pi N_r)}{\rho N_r^3 D^5}. \tag{1}$$

Here, P, D, T, ρ, and Nr are the specific power consumption (W), the blade diameter (m), the torque exerted on the blade (Nm), the density ($kg \cdot m^{-3}$), and the stirring speed of the blade (s^{-1}), respectively. It was confirmed by flow visualization that the particle movement was restricted to a region immediately around the rotating blade. Thus, the flow state can be considered as a laminar flow and the power number decreases inversely proportional to the Reynolds number [17,19], Re, suggesting that:

$$N_p \cdot Re = k \tag{2}$$

where, k is a constant and can be considered as the shape characteristic of the blade [17]. This derivation has even been applied to the characterizations of fluids such as gas/liquid–solid slurry systems [17,18]. From Eqs. (1) and (2), the apparent viscosity can be derived as:

$$\eta = \frac{\pi^2}{kD^2} \cdot \frac{T}{\pi N_r D} \tag{3}$$

where, η termed in this paper as the apparent viscosity of the solid particles, represents the resistance against movement. As shown in Eq. (3), $\frac{T}{\pi N_r D}$ reflects the torque (T) caused by per unit line velocity ($\pi N_r D$) change of the blade tip, which physically agrees well with the concept of resisting ability of particles against movement. While, item of $\frac{\pi^2}{kD^2}$ was determined by the shape and size of the blade tip. Further, for simplicity, let:

$$A = \frac{\pi^2}{kD^2}. \tag{4}$$

Then,

$$\eta = A \cdot \frac{T}{\pi N_r D}. \tag{5}$$

Here, for a fixed blade type, A is constant and independent of other experimental conditions. In this work, the value of A in Eq. (5) was initially acquired by using a Newtonian fluid with a known viscosity (the details are shown in the next part) and then Eq. (5) was utilized to estimate the viscosity of other fluids.

2.2. Apparatus

A traditional rotating viscometer equipped with a large torque sensor (0–0.5 N·m) was utilized as shown in Fig. 1(a), where a typical cylinder probe was transformed into a blade-type probe, as illustrated in Fig. 1(b). In this research, three blade-type probes were prepared, and the angle of the blade tip with the horizontal surface was 0°, 5°, and 10°, as shown in Fig. 2. This equipment has two heating devices, which can be selected based on different needs. Oil bath pot and iron chromium aluminum wire resistance furnace can be used in temperatures below 200 °C and ranging from 200 °C to 1000 °C, respectively.

2.3. Test of reference fluids with known viscosity

The torque of various fluids (provided by the Brookfield Company) with known viscosity at 25 °C was measured using the rotating viscometer in Fig. 1(a), which was equipped with a blade-type probe. This was done to obtain the value of A in Eq. (5). Castor oil and several kinds of syrup solutions were also used for this purpose, where their viscosities were measured using the rotating viscometer equipped with a standard cylinder probe. During these experiments, 100 mL of each fluid was put into a transparent crucible with a height 70 mm and a radius 25 mm. A water bath was used to maintain the temperature of the sample at 25 °C. When the blade was rotated inside each fluid at the target speed, the torque exerted could be acquired from the viscometer.

By using the above method, the torque data (the blade in Fig. 2(b) was used) of several reference fluids with known viscosity were obtained under varying situations. The dependence of the viscosity for different reference fluids on $\frac{T}{\pi N_r D}$ is shown in Fig. 3. Good linear plots with nearly zero intercepts are observed over two viscosity ranges: 0.66–12.5 Pa·s and 12.5–100 Pa·s. For each viscosity range, formulas Eqs. (6) and (7) were obtained, respectively. And the values for A were determined to be 650 and 775 accordingly. It suggested that by using the fixed probe in this experiment, A is independent of experimental conditions. This indicated that when rotating this blade inside a fluid, if the torque acting on the blade is measured at a fixed speed, the viscosity η could be obtained by Eq. (6) or Eq. (7) with different application ranges. This method is