



Prediction of defluidization behavior of iron powder in a fluidized bed at elevated temperatures: Theoretical model and experimental verification



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ABSTRACT

A mathematical model of force balance was developed to describe the fluidization characteristics and predict the high-temperature defluidization behavior of iron powders. The calculation was focused on the evolution of the forces acting on particles with temperature based on the surface viscosity and bubble motion. The parameters in the model were obtained by a statistical regression method. Comparing with the experimental data, the simulated results of the defluidization temperature represented a good agreement. This model explained theoretically the dependence of defluidization behavior on the fluidizing gas velocity and gas properties. Accordingly, the stable fluidization and the defluidization regions were determined in the operating phase diagram of fluidization.

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1. Introduction

As ideal reactors to treat fine raw materials, fluidized beds have great application potential in metallurgy industry, especially in iron-making, due to better utilization of energy and lower pollutant emissions [1,2]. However, fluidized beds were often limited because of the serious problem of high-temperature defluidization resulting from the metallization of ore and the formation of the eutectic phases [2]. Therefore, the particle behavior in fluidized beds and its effect on agglomeration have received extensive research attention.

Defluidization phenomenon was attributed to an increase of particle stickiness at elevated temperature, and the agglomeration tendency depended strongly on the physical and chemical characteristics of the bed materials at a high temperature range [3–6]. Agglomeration mechanisms are mainly of two types (1) plastic–viscous flow and sintering caused by surface/volume diffusion of the bed materials; and (2) formation of liquid phase by melting and chemical reactions. Many operating parameters can affect agglomeration/defluidization including gas velocity, particle size and distribution, gas distribution and reactor structure. With a certain fluidized-bed material, when the bed temperature reached a point at which the particle surface began to sinter or soften, the bed defluidization occurred. If the adhesion force caused by the inter-particle bond (sintered neck) had sufficient strength to withstand the breaking force imposed by the movement of particles

and gas flow, the defluidization appeared. However, it is difficult to predict accurately and thus prevent the appearance of defluidization. Therefore, the mechanistic models are needed to reliably predict under what conditions the defluidization will occur.

Several mathematical models have been developed to predict the defluidization behavior at high temperatures. Tardos et al. [7,8] compared the breaking forces and the cohesive force acting on agglomerates and particles to predict the limiting velocity to defluidize. Moseley et al. [9] developed a model of energy balance to calculate the defluidization velocity as a function of temperature. Based on the surface reaction of eutectics, agglomeration models for fluidized bed combustors were developed to predict defluidization time by employing mass balance and force balance combined with a regression analysis [10–12]. Valverde et al. [13] proposed a simple equation to estimate agglomerate size derived from the balance between the local shear force on the particle attached at the outer layer of the agglomerate and the inter-particle adhesion force. An investigation of the sintering mechanism of iron particles under reducing conditions has been reported by Mikami et al. [14], revealing the relation between the bed temperature and the minimum gas fluidizing velocity required to prevent defluidization. In the case of metal particles, the type of material transport to form a sintered neck was surface or volume diffusion. Seville and Knight [15,16] successfully predicted the temperature dependence of the bed breaking fluidization velocity from the activation energy for surface diffusion.

However, in a fluidized bed system, the intensively mixed particles did not have enough contact time to form a sintered neck, and thus the adhesive force by sintering was insufficient for particle agglomeration. And these predictions for the fluidizing velocity [14–16] were

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based on the experiments conducted by heat-treating the bed materials in a fixed bed state, and thus did not well reflect the actual particle motion, especially the process from stable fluidization to sudden defluidization. Therefore, the agglomeration/defluidization was not explained fully by the surface diffusion mechanism. According to our previous work [17], the flowability and viscosity on the surface of solid appeared at temperature very below the fusion point of material, and the evolution of the adhesion force related to the surface viscosity was better to reflect the change of the inter-particle force with temperature and simulate the defluidization process. Therefore, the theoretical treatment of defluidization based previously on a surface diffusion mechanism can be suitably modified by a plastic–viscous flow mechanism and then applied to sintering. In addition, previous agglomeration models for iron powders were focused on the relationship between the bed temperature and the fluidizing velocity required to prevent defluidization [14,16]. However, no mathematical models are reported to simulate the defluidization process, especially to predict under what operating conditions defluidization will occur in fluidized beds. An effective defluidization model is useful to control or inhibit bed agglomeration in the fluidized bed operations.

Therefore, the aim of this work is modeling the high-temperature defluidization behavior of iron powders involving the effects of gas velocity and gas properties. By analyzing the experimental data with a statistical regression, a force balance model is developed to describe the defluidization processes in a fluidized bed, by which the fluidization operations (temperature, gas velocity and gas properties) where the defluidization appears are predicted. And then the fluidization operation diagram is defined.

2. Modeling defluidization phenomena

2.1. Assumptions

The fluidization behavior of bed particles depended on the forces acting on them. Therefore, this model employed the balance of cohesive and segregate forces to simulate agglomeration/defluidization and predict the defluidization temperature. Taking account of particle moving, colliding, coalescing and breaking in a fluidized bed system, the following assumptions are made to describe the main characteristics of the defluidization phenomena based on the previously described experimental results:

1. Bed material particles are spherical and in uniform size.
2. The fluidizing gases do not react with the bed particles, and no coating layer forms on the surface.
3. The adhesive force between two particles arises from surface viscosity and is determined by the plastic–viscous flow mechanism.
4. The force against agglomeration is the drag force acted on particles due to bubble motion.
5. If the adhesive force equals or exceeds the segregation force, the bed defluidization appears.

2.2. Model formulation

As the temperature increases, the effect of adhesion force becomes dominant due to surface softening, resulting in a quick defluidization. The adhesive force associated with the plastic–viscous flow mechanism can be described by:

$$F_{ad} = \pi b^2 \sigma \quad (1)$$

where σ represents the tensile stress of the agglomerate and b is the radius of the connection between the particles.

According to Benson et al. [18], the tensile stress of the agglomerate is

$$\sigma = \frac{At}{\mu_s d_p} \quad (2)$$

where A is a constant; t represents the connect time of two particles; d_p is the mean size of particle; and μ_s is the surface viscosity of the particle materials.

In a fluidized bed where particles are intermittently mixed, the contact time of particles is dependent on the bubbles' motion. The residence time is required to be sufficiently long for particle connection to form agglomerates. Therefore, in this study the connect time of two particles was considered as the characteristic residence time for which particles within a fluidized bed remain in contact with each other as reported by Seville et al. [15,16]:

$$t = \frac{\beta}{(U_g - U_{mf})} \quad (3)$$

where β is a proportional coefficient; U_g is the operating gas velocity; and U_{mf} is the minimum fluidization velocity in non-sintering conditions, which is calculated by the simplified Wen–Yu equation:

$$U_{mf} = \frac{d_p^2 (\rho_s - \rho_g)}{1650 \mu_g} g \quad (4)$$

where ρ_g and μ_g are the gas density and viscosity respectively; and ρ_s is the particle density.

The surface viscosity of solid is a function of temperature and is assumed to be estimated by the Arrhenius' expression [15]:

$$\mu_s = \mu_{s0} \exp\left(\frac{E_s}{RT}\right) \quad (5)$$

where E_s is the activation energy for the surface viscosity and T is the absolute temperature.

To accurately predict the segregate force, this model employs the drag force acting on particles to represent the force against agglomeration, which is related to the effect of the particle size, gas velocity and gas properties. The expression is:

$$F_d = \alpha C_d \frac{\pi}{8} d_p^2 \rho_g U_g^2 \quad (6)$$

$$C_d = \frac{24}{Re} \left(1 + 0.173 Re^{0.657}\right) + \frac{0.413}{1 + 16300 Re^{-1.09}} \quad (7)$$

[19]

$$Re = \frac{d_p \rho_g U_g}{\mu_g} \quad (8)$$

where α is a proportional coefficient, representing the unknown errors in this equation. C_d is the drag coefficient; and Re is Reynolds number.

If the adhesive force equals the drag force, the bed is defluidized:

$$\frac{\pi A \beta b^2}{\mu_s d_p (U_g - U_{mf})} = \alpha C_d \frac{\pi}{8} d_p^2 \rho_g U_g^2 \quad (9)$$

In this work, we defined two number groups N_a and N_d , representing the adhesion force and the drag force respectively:

$$N_a = \frac{\pi}{\mu_s d_p (U_g - U_{mf})} \quad (10)$$

$$N_d = C_d \frac{\pi}{8} d_p^2 \rho_g U_g^2 \quad (11)$$

Therefore, the defluidization criterion (Eq. (9)) can be expressed as:

$$N_a = K \cdot N_d \quad (12)$$

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