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A new prediction method for the viscosity of the molten coal slag. Part 1: The effect of particle morphology on the suspension viscosity

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ABSTRACT

Viscosity is the key factor affecting the flowability of molten coal slag in the entrained flow gasifier. The volume fraction and morphology of solid phase in slag are important factors affecting the slag viscosity. In this study, the malt syrup and the particles with different sizes and morphologies were chosen as the simulation medium to study the effect of particle morphology on the suspension viscosity. The influences of size, shape and aspect ratio of solid particles on the suspension viscosity were considered. It was concluded that the suspension viscosity increased with the decrease of the particle size. The suspension viscosity increased with the increase of the aspect ratio of the particles. This phenomenon was more obvious under the high volume fraction of solid phase. With the same size and aspect ratio, the non-spherical particles had greater effect on the suspension viscosity than spherical particles. A correction factor was used to modify the viscosity model with the consideration of particle size, shape and aspect ratio. The prediction results of new modified viscosity model of the suspension finally showed good agreement with the measured experimental data.

1. Introduction

Entrained flow gasification technology was received widely application in the field of energy conversion. It allows for various combinations of electricity, liquid fuels, hydrogen, chemicals and heat with the characters of high efficiency and fuel flexibility [1]. Entrained flow gasifier usually operates at a high temperature (above the ash flow temperature) to ensure a good slagging condition for the stable operation [2,3]. The slag viscosity is the key factor in determining whether the slagging condition is stable and smooth.

The measurement of the viscosity of molten slag is significant not only for the theoretical research on melt, but also for the industrial application. Slag type with suitable fluidity at the low operation temperature for saving energy consumption is required to study [4]. The viscosity of slag with low melting point should be investigated to develop an improved gasification operation at low temperature. Molten slag is a solid-liquid two-phase mixture and solid particles do exist in slag in gasification processes. The viscosity of fully liquid slag increased with decreasing temperature, and the temperature dependence of the viscosity was usually expressed in the form of the Arrhenius relationship. With the precipitation of crystals from molten slag below the melting point, the slag behaved as a non-Newtonian fluid and the viscosity showed a sharp increase near the melting point [5]. Therefore, the characteristics of crystal precipitation during the cooling process of the molten slag were studied.

Xuan et al. [6–9] studied the influences of CaO, Fe_2O_3, SiO_2/Al_2O_3 on crystallization characteristics of synthetic coal slags. With the increase of CaO, crystallization of the slags became obvious, especially in which with a calcium content range between 15% and 35%. With a higher ratio of Fe_2O_3, more crystallization heat was released and the crystallization shifted to a higher temperature, potentially leading to a higher T_{cv} (Critical viscosity temperature) in viscosity. The kinetics under isothermal 1100 °C show that the growth rate of crystals increases with the addition of iron oxide. As the S/A ratio increased between the range of 1.5–3.5, the crystal was clear and energy barrier was significantly lowered and the crystallization ratio increased. Shen et al. [10] studied the effect of cooling process on the generation and growth of crystals in coal slag. Low cooling rate was beneficial to the generation of the crystals and long residence time below the initial crystallization temperature promoted the generation and growth of crystal. The influence of internal and external factors on slag viscosity was studied by Kong et al. [11–13]. They found that viscosities of glassy and

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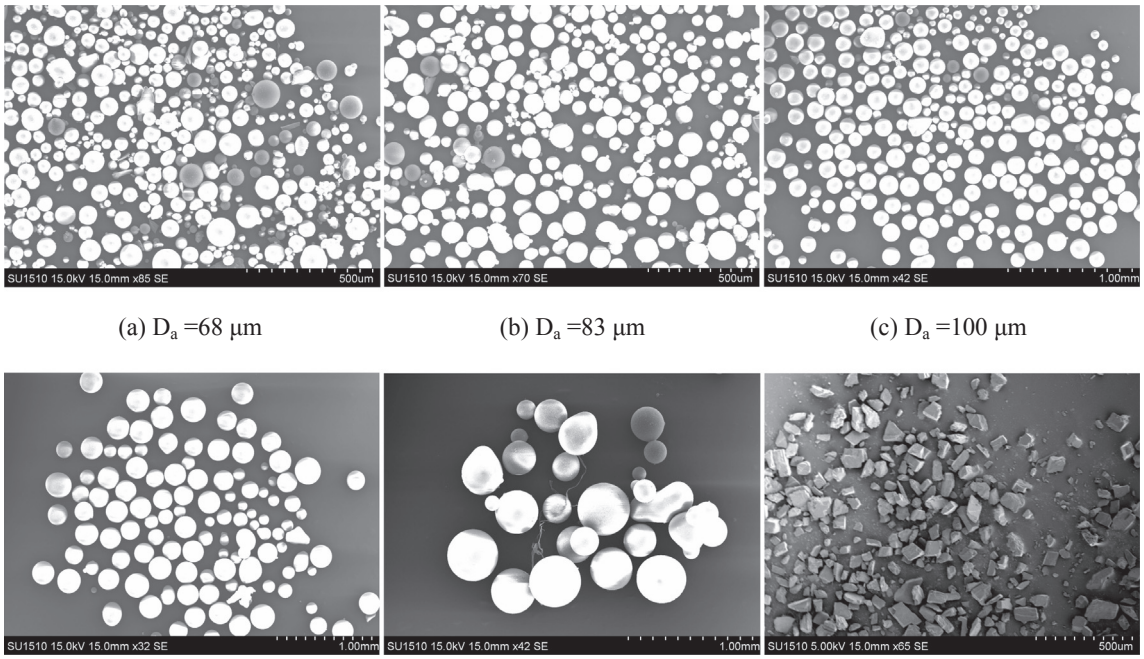

(a) D_a =68 μm (b) D_a =83 μm (c) D_a =100 μm

(d) D_a =187 μm (e) D_a =250 μm (f) D_a =187 μm

Fig. 1. The SEM images of particles with different sizes, (a)-(e) glass beads, (f) quartz sand particles.

crystalline slag both decreased with increasing cooling rate. The viscosity of the molten slag increased with the increasing the mass fraction of residual carbon. Kondratiev et al. [14] proposed chemical components such as P_2O_5, B_2O_3 possessed strong, highly covalent metal-oxygen bonds, leading to high liquid viscosities. Ilyushechkin et al. [15] concluded that slag viscosity depended on the slag bulk composition above the liquid temperature line. Zhang et al. [16] found that the viscosity of molten slag increased as increasing the volume fraction of TiC. Many researchers also proposed other factors (constant temperature, continuous cooling and different kinds of mineral) that affect the crystallization [17–21]. Owing to the difficulties in measurement, the viscosity of two-phase mixtures was hardly investigated. In view of the importance of slag viscosity in the optimization of gasification processes, researchers have used different models to estimate the viscosity of solid-liquid mixtures.

Early in the twentieth century, Einstein derived a linear equation about suspension viscosity based on Stokes equation [22,23]. Experiments were carried out to examine the applicability of Einstein's equation. The results demonstrated that this model could be only applied to dilute suspension [22]. For this reason, Simha used cell method to estimate the viscosity of liquid containing solid particles [24]. Following this approach, Happel [25], Zholkovskiy et al. [26], Sengun et al. [27], Malomuzh et al. [28], and Sherwood [29] had proposed modified models. Since the above models were derived from different boundary conditions, the prediction results were quite different at high particle volume fraction.

A number of semi-empirical models have been developed based on experiment data [30–33]. Jung et al. [34] proposed a comprehensive viscosity model for micro magnetic particles dispersed in silicone oil. The viscosity increased with the solid phase volume fraction. The magnetic field decreased with the shear rate and the temperature. The effect of temperature and solid phase volume fraction was well described by the Arrhenius model and the Krieger and Dougherty model [34]. The multiplied form of magneto rheological model was verified by the experiment data, and it was very useful for the prediction of shear viscosity under various operating conditions. Thionnet et al. [35] put forward the influence of the volume fraction, size and surface coating of hard spheres on the microstructure and rheological properties of model in mozzarella cheese. However, most of the experiment data had been generated using aqueous solutions. The big difference in viscosity between slag (usually > 0.1 Pa.s) and aqueous solution made the application of any of these models to slag system uncertain.

Koudratiev et al. [36] calculated the fractions of solid phase using F.A.C.T for some reported slags [37] and applied Roscoe model [31] to the two phase mixtures. The modified parameters for Roscoe equation with better accuracy and applicability were also reported. Wright et al. [38] measured the slag viscosity with either Al_2O_3, MgO or Fe_3O_4 particles. Great dependence of viscosity on rotation speed was reported when the fraction of particles was above 0.04.

A number of literatures studied the relationship between the suspension viscosity and the solid phase volume fraction, and obtained a series of models. However, most of the models assumed that the particles were spherical and nearly spherical, which was serious different from the actual situation. The aim of the research was to get a more accurate prediction model of the suspension viscosity. In this paper, the malt syrup and the particles with different size and morphology were chosen as the simulation medium to study. The effects of particle size, shape and aspect ratio of solid particles on the suspension viscosity were considered. Finally, a modified prediction model of slag viscosity were proposed and compared with the experimental data.

2. Experiment

2.1. Experiment material

The solvent used in the experiment was the syrup with a concentration of 70%. The density of the syrup was 1.28 g/cm^3 at 25 °C. The solid particles added to the syrup were glass beads (SiO_2 > 90%), wollastonite powders ($Ca_3(Si_3O_9)$) and quartz sand particles (SiO_2 > 67%). The density of glass beads was 1.5 g/cm^3. The average diameter of glass beads were screened to 68, 83, 100, 187 and 250 μm respectively. The density of wollastonite particle was 1.3 g/cm^3 and its shape was acicular, the average particle size were screened to 12, 18.75 and 37.5 μm respectively. The aspect ratio of the wollastonite particles

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