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Influence of rheological properties on air-blast atomization of coal water slurry

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ABSTRACT

An experimental investigation is conducted to determine the effect of rheological properties (viscoelasticity) on the air-blast atomization of coal water slurry. In air-blast atomization, aerodynamic force causes the liquid to deform and breakup. To observe breakup morphology of coal water slurry atomization, a high speed digital camera is used at various operating conditions. In this test, primary atomization is the condition that a cylindrical liquid jet surrounded by a coaxial annular airflow, and secondary atomization is the process that a liquid drop encounters a continuous air jet. The results show that the viscoelasticity of coal water slurry has great influence on the breakup morphology, breakup length, frequency characteristics. The corresponding correlations for these characteristics also are developed.

1. Introduction

Coal water slurry (CWS) is a fuel which consists of coal particles suspended in water, which is widely used in coal combustion and gasification. Coal gasification is now enjoying a considerable renaissance after substantial technical development [1]. At present there are GE Energy (Texaco) gasification process [2], OMB (opposed multi-burner) gasification process [3,4], etc. The efficiency of gasification is dependent on mass transport rate, making it important to understand the fundamentals of CWS atomization [5]. CWS is a kind of non-Newtonian slurry [6–8], and the atomization of CWS is remarkably complex and difficult.

Atomization can make continuous liquid into dispersed phase, which is of importance in many industrial processes. Therefore, the process has been studied extensively both theoretically and experimentally [9–17]. When the liquid jet is injected into the coflowing high speed airflow, the liquid jet breaks up owing to momentum transfer from the gas to the liquid. This type of breakup is often referred to as air-blast atomization [18]. Air-blast atomization is one of the most important types of atomization. Air-blast atomization process usually consists of the initial removal of liquid mass from the surface to form large liquid drops, and the subsequent break up of these drops into tiny droplets. The phenomena are respectively known as primary and secondary breakup, or called primary and secondary atomization [19,20].

With the development of high-speed camera technology, morphology analyses are common in the research of fluid mechanics, which can help us to learn more knowledge on physical mechanism of atomization. There are numerous morphology researches of coaxial two-fluid air-blast atomization in literature, which mainly focus on Newtonian liquid, such as water [21–24]. Atomization of non-Newtonian slurry plays a key role in many practical processes, and during atomization there are significant differences between Newtonian liquid and non-Newtonian slurry. So many researchers also focus on atomization of non-Newtonian slurry. Krishna [25] summarized the early investigations of slurry atomization. Then, there are some reports on CWS atomization, which mainly focus on the atomizer performance and mean droplet diameter after atomization [26–33].

Viscoelasticity is the property of materials that exhibit both viscous and elastic characteristics when undergoing deformation, which is common in polymer solution, suspension and slurry,

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Nomenclature

a	acceleration
D_0	initial drop diameter in secondary atomization
D_1	diameter of atomizer central circular orifice in primary atomization
D_2	inner diameter of atomizer coaxial air annular orifice in primary atomization
D_3	outer diameter of atomizer coaxial air annular orifice in primary atomization
D_{max}	the maximum cross stream diameter of the drop during deformation process in secondary atomization
f	liquid jet oscillation frequency
G'	elastic modulus or storage modulus
G''	viscous modulus
L_b	liquid jet breakup length (or named intact length, core length)
M	momentum flux mass ratio per unit volume (or called momentum flux ratio), $M = \frac{\rho_g u_g^2}{\rho_l u_l^2}$
n	number of wave crests
N_1	first normal stress difference
N_2	second normal stress difference
Oh_p	Ohnesorge number in primary atomization, $Oh_p = \frac{\mu}{\sqrt{\rho_l D_1 \sigma}}$
Oh_s	Ohnesorge number in secondary atomization, $Oh_s = \frac{\mu}{\sqrt{\rho_l D_0 \sigma}}$
p	pressure
St	Strouhal number, $St = \frac{fD_1}{u_l}$
T	non-dimensional time in secondary atomization, $T = \frac{u_g t}{D_0(\rho_l/\rho_g)^{1/2}}$
t_0	the time of liquid breakup
t	dimensional time
u_g	air velocity
u_l	liquid velocity
u_e	entrainment velocity
u_c	convection velocity of the liquid surface waves (interface)
We_p	Weber number in primary atomization, $We_p = \frac{\rho_g (u_g - u_l)^2 D_1}{\sigma}$
We_s	Weber number in secondary atomization, $We_s = \frac{\rho_g u_g^2 D_0}{\sigma}$
X_p	the ratio of first normal stress difference to surface tension force in primary atomization, $X_p = \frac{N_1}{\sigma D_1}$
X_s	the ratio of first normal stress difference to surface tension force in secondary atomization, $X_s = \frac{N_1}{\sigma D_0}$
ρ_l	liquid density
ρ_g	air density
σ	surface tension
μ	liquid dynamic viscosity
τ	shear stress
γ	shear rate
τ_{11}	the stress along the flow direction
τ_{22}	the stress which is perpendicular to the flow direction
τ_{rr}	the stress along the flow direction in cylindrical coordinate
$\tau_{\theta\theta}$	the stress which is perpendicular to the flow direction in cylindrical coordinate
λ_K	classical Kelvin–Helmholtz instability wavelength
λ_{KH}	modified Kelvin–Helmholtz instability wavelength
λ_{RT}	wavelength of Rayleigh–Taylor instability

etc. [34–39]. These studies in literature [40–49] show the significant impact of viscoelasticity on liquid breakup and atomization. Experimental results indicate that the breakup behavior of viscoelastic liquid is different from Newtonian liquids, and there are also many interesting physical phenomena. However, the breakup and atomization of viscoelastic liquid, especially CWS, has not yet been fully quantified. So much work remains to be done in this area.

Motivated by the studies cited above, we conducted an experimental investigation on the primary atomization of coaxial air-CWS jets, and secondary atomization of a liquid drop encounters a continuous air jet. A high-speed digital camera was used combined with a back illumination method, to obtain images of CWS deformation and breakup. CWS breakup morphology, breakup length, frequency characteristics were analyzed in this article.

2. Experimental apparatus and methodology

2.1. CWS properties

Experiments are conducted at atmospheric pressure and room temperature, and the working fluids are CWS and air. Coal particle size cumulative distributions are given in Fig. 1a. In this test the coal type is bituminous coal, whose density is 1490 kg/m^3. The basic shapes of the particles are shown in Fig. 1b. Scanning electron microscope images of the particles also show a wide distribution of sizes of blocky particles. The particle size distribution is determined by automatic laser granularity analyzer (Malvern mastersizer 2000). There are three kinds of CWS, whose physical properties and experimental conditions are shown in Table 1. The concentration of coal water slurry (CWS) is shown in Table 1. Here ρ_l is CWS density, σ is surface tension, μ is CWS viscosity, γ is shear rate. CWS rheological behaviors are shown in Figs. 2 and 3. And the storage modulus in oscillatory test is shown in Fig. 3. The measurements of rheological properties are performed using rotating-type rheometer (Malvern Bohlin). The effects of volume fraction on viscosity are described using Krieger–Dougherty model as shown in Fig. 2b, $\mu = \mu_0(1 - \phi/\phi_j)^{-n\cdot\phi_j}$, where μ_0 is the solvent viscosity (water), ϕ_j is the jamming packing fraction, n is the intrinsic viscosity. The water used is deionized water, whose pH is 7. Based on the experimental results, we obtained that ϕ_j = 0.62 and n = 4.5. The yield stress of CWS is shown in Table 1.

In order to improving rheological characteristic of CWS, there are some chemical additives used. The dispersant is sodium

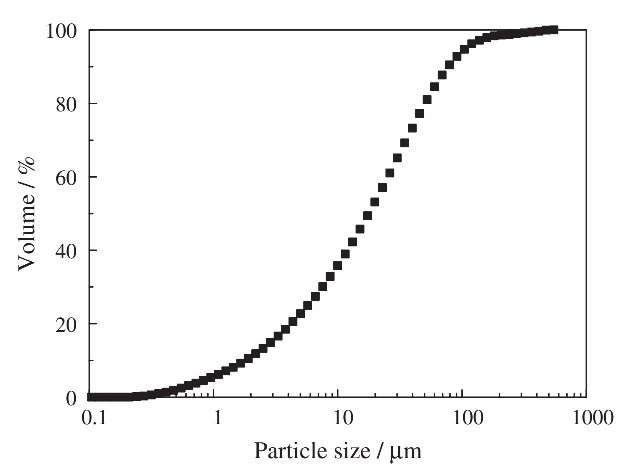

Fig. 1a. Coal size volume cumulative distribution.