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Factors influencing the characterization of bubbles produced by coaxial gas–particle jet flow

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HIGHLIGHTS

- ▶ The influencing factors of the bubble-formation process have been studied in detail.
- ▶ A criterion has been proposed to determine the formation of the bubbles.
- ▶ The main cause of bubbling has been further verified by comparison.

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ABSTRACT

The effect of particle mass flow rate and annular channel thickness on the formation and characteristics of the bubbles is investigated experimentally by high-speed digital photography. A criterion is proposed to determine the emergence of the bubbles. The experimental results demonstrate that the particle mass flow rate and the annular channel thickness are both crucial factors for the bubble-formation process. The bubble size, bubble growth rates and bubbling frequency are investigated by analyzing a large number of images. The radial growth rate of the bubble is still governed by the superficial air jet velocity. In addition, the radial velocity difference between the gas and particle phase is confirmed to be the main cause of bubbling.

1. Introduction

Gas–particle two-phase flows are frequently encountered in many energy-related processes [1–3]. The particle behaviors in two-phase flows, such as the dispersion of particles, are of great importance in above processes. To enhance the understanding of particle behaviors, many studies have been conducted in this field [4–10]. Two coaxial jet configurations are commonly used in the gasification process of pulverized coal, i.e., the particle-centered type and the gas-centered type. Recently, the dispersion characteristics of a granular jet surrounded by an annular air jet, such as the undisturbed length, dispersion length and dispersion angle have been investigated by Liu et al. [11,12], and three typical dispersion modes have been identified. In our previous work [13], we studied the flow features of an annular granular jet dispersed by a central air jet experimentally. The particle bubble (hereinafter referred to as "bubble"), which was similar to the liquid bubble observed in the gas–liquid coaxial jets [14–18], was found to be periodically formed. The dispersion angle of granular jet was mainly governed by the radial growth rate of the bubble, which revealed that, in the near field, the formation of the bubble had a significant influence on particle dispersion.

However, in our earlier work [13], the influencing factors of the bubbling characteristics, such as the particle mass flow rate and the nozzle geometry, were not discussed in detail. Thus, the current work focuses on the effect of particle mass flow rate and annular channel thickness on the formation and characterization of bubbles. The different situations explored here permit us to clarify the importance of the two factors in the bubble-formation process and propose a criterion to determine the emergence of bubbles. In addition, the main reason of bubbling is further discussed by comparison.

2. Experimental setup

The experimental setup and instrumentation are the same as those in our earlier work [13]. Air from a blower flows out as the

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Nomenclature

d	central channel diameter of the nozzle (mm)
d_p	particle diameter (μm)
D_i, D_o	inner and outer diameters of the annular channel of the nozzle (mm)
f_b	bubbling frequency (Hz)
l	length of the straight section of the nozzle (mm)
L_x, L_y	axial and radial bubble size (mm)
L_{xe}, L_{ye}	axial and radial bubble size at the end of the bubbling period (mm)
m_g	air mass flow rate (kg/s)
m_p	particle mass flow rate (kg/s)
M	gas–particle momentum ratio
M_g	gas momentum (kg m/s^2)
M_p	particle momentum (kg m/s^2)
Re	Reynolds number of inner gas flow
S	swirl number
St	Strouhal number
t	time (s)
u_{g0}	superficial air jet velocity (m/s)
u_{p0}	superficial particle jet velocity (m/s)
u_x, u_y	axial and radial growth rates of the initial bubble (m/s)

Greek symbols

α	convergence angle of outer nozzle (°)
β	convergence angle of inner nozzle (°)
δ	annular channel thickness (mm)
μ_g	air dynamic viscosity (Pa s)
ρ_b	particle bulk density (kg/m^3)
ρ_g	air density (kg/m^3)
ρ_p	particle density (kg/m^3)

center jet, and particles stored in a hopper as the annular jet. Due to the characteristics of granular matter [19], the mass flow rate of the particles is mainly controlled by the pressure in the hopper, thus different mass flow rates of particles can be obtained by changing the pressure in the hopper. Similar to Ref. [13], a high-speed digital camera is used to record the dispersion process of granular jet, and ImageJ [20] is employed to analyze the images.

In this work, five coaxial two-channel nozzles are adopted. Three of them are convergent nozzles, as shown schematically in Fig. 1a. The difference among the three convergent nozzles is the thickness of the annular channel. To explore the main reason of the formation of bubbles, nozzle (b) and nozzle (c) are used in our experiments. The configuration of nozzle (b) is similar to that of the convergent nozzles except a straight section which is followed by the convergent section. And the difference between the configurations of nozzle (b) and nozzle (c) is the addition of a swirler. The configuration of this swirler with a swirl number of $S = 1.01$ is the same as that of the swirler 3 adopted in Ref. [13]. The swirl number S, which denotes the degree of swirl for a swirling jet, is a dimensionless number representing axial flux of angular momentum to divided by the product of nozzle exit radius and axial flux of axial momentum. The calculation expression of S is also the same as that presented in Ref. [13]. The detailed parameters of the nozzles are summarized in Table 1.

The Reynolds number of the air is defined as

$$\mathrm{Re} = \frac{d u_{g0} \rho_g}{\mu_g}, \tag{1}$$

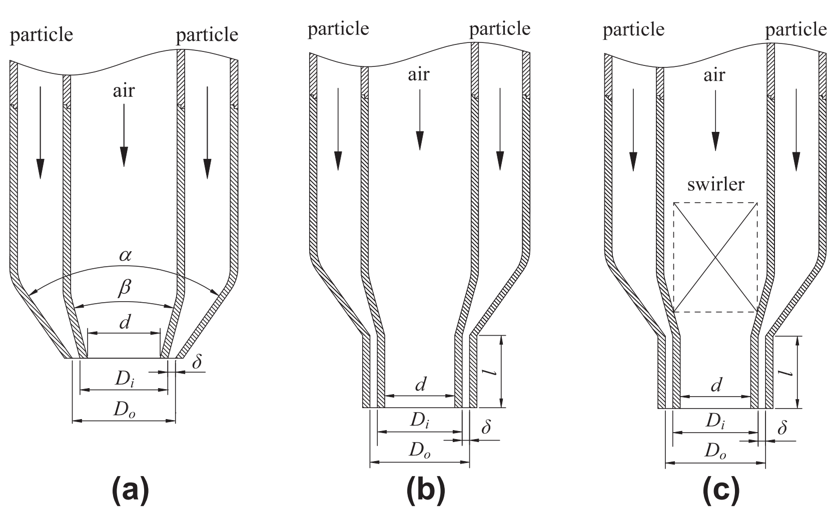

Fig. 1. Configuration of coaxial two-channel nozzles.

Table 1
Geometrical parameters of nozzles.

Serial number	d (mm)	D_i (mm)	D_o (mm)	δ (mm)	α (°)	β (°)	S	l (mm)
Nozzle 1	20	24	27	1.5	70	30	0	–
Nozzle 2	20	24	28	2.0	70	30	0	–
Nozzle 3	20	24	29	2.5	70	30	0	–
Nozzle 4	20	24	27	1.5	0	0	0	20
Nozzle 5	20	24	27	1.5	0	0	1.01	20