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Local flow regime and bubble size distribution in the slender particle-containing scrubbing-cooling chamber of an entrained-flow gasifier

Xin Peng, Yifei Wang *, Zongyao Wei, Guangsuo Yu, Fuchen Wang

Key Laboratory of Coal Gasification and Energy Chemical Engineering of Ministry of Education, East China University of Science and Technology, Shanghai 200237, PR China

HIGHLIGHTS

- A modified Kataoka-Ishii bubbly flow semi-empirical correlation was developed.
- Bubbly and cap-bubbly flows were observed in a local flow regime map.
- CLDs were transformed into BSDs by decomposing and estimating the measured CLDs.
- The bubble size for the demarcation between small and large bubbles was 2 mm.
- Fiber number density was used to characterize the variations of fiber aspect ratio.

ARTICLE INFO

ABSTRACT

A dual-tip conductivity probe was used to measure local radial gas holdups and bubble chord lengths to study the local flow regime and bubble size distribution in a scrubbing-cooling chamber cold model apparatus containing slender particles. The results showed that the cross-section averaging gas holdups with different fiber volume fractions and aspect ratios could be estimated within errors of ±10% using the modified Kataoka-Ishii bubbly flow semi-empirical correlation at superficial gas velocities ranging from 0.074 m/s to 0.37 m/s. The local flow regime map showed that an obvious bubbly flow formed near the inner wall of the liquid bath due to the effect of wall shear stress, while a cap-bubbly flow formed in other annulus regions due to the emergence of cap bubbles. Chord length distributions were transformed into bubble size distributions by decomposing the measured chord length distributions and estimating the bubble shape factors. Bubble size was categorized into two types—small spherical and large non-spherical bubbles—depending on if the equivalent diameter of the bubbles was smaller or larger than 2 mm. Liquid turbulence, shear stress between the fluid and the wall and liquid backmixing were enhanced by increasing the superficial gas velocity, which affected the size distributions of rising and descending bubbles as well as that of bubble populations. The extent of turbulence suppression and "fiber separation walls" varied with the fiber volume fractions, which affected the bubble size distribution in different regions. The fiber number density characterizing the variation of the fiber aspect ratio with different fiber diameter and length was used to study the bubble size distribution. The bubble size distribution at different aspect ratios was affected by interactions among fibers, bubbles, the fluid and the wall.

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1. Introduction

Large-scale coal gasification is the key technology for clean and efficient coal utilization. It is also the leading technology in the development of many industrial processes such as coal-based chemical synthesis, liquid fuel synthesis, advanced IGCC (integrated gasification combined cycle) power generation and poly-cogeneration. The entrained-flow gasifier, the mainstream technology for the development of coal gasification, has a high

gasification temperature and pressure, can be used for large-scale production and is widely adaptable for many coal types (Wang et al., 2009). In an opposed multi-burner (OMB) gasifier, the scrubbing-cooling chamber which plays an important role in the washing and cooling of high-temperature crude coal gas, is composed of a spray bed and an annular bubbling bed (Yu et al., 2011). High-temperature crude coal gas with molten slags flows downstream along the scrubbing-cooling tube and then enters a liquid bath, in which gas-liquid-solid separation is performed. The structures and flow regimes of the scrubbing-cooling chamber are extremely complicated and most studies have been carried out on gas-liquid two-phase flow, such as gas-liquid separation (Wang

Nomenclature

Symbol

A_1, A_2	correction coefficient (–)
a_r	fiber aspect ratio (–)
C_0	distribution parameter (–)
c_s	fiber volume fraction (%)
D	equivalent bubble diameter (mm)
$D_{CL,max}$	maximum chord length (mm)
D_H	hydraulic diameter (m)
D_H^*	dimensionless diameter (–)
$D_{H,cr}^*$	critical dimensionless diameter (–)
D_{in}	inner diameter of the scrubbing-cooling chamber (mm)
D_{max}	maximum spherical bubble diameter (mm)
d_{out}	external diameter of the scrubbing-cooling tube (mm)
d_p	fiber diameter (mm)
dt	bubble lag time (s)
Eo	Eötvös dimensionless number (–)
g	gravity acceleration (m/s^2)
l	tip distance (mm)
l_p	fiber length (mm)
Mo	Morton dimensionless number (–)
N_f	fiber number density (1/m^3)
$N_{\mu l}$	viscosity number (–)
P_a, P_b	conductivity probe tip
$P_b(R)$	size distribution of bubbles touching the probe (mm^{-1})
$P_c(y)$	size distribution of measured chord lengths (mm^{-1})
R, d	bubble radius (mm)
R_{in}	external radius of the downcomer
R_{out}	inner radius of the scrubbing-cooling chamber
t	sampling time (s)

U_g	superficial gas velocity (m/s)
U_g^+	dimensionless superficial liquid velocity (–)
V_a, V_b	level voltage (V)
V_{gj}	weighted mean drift velocity (m/s)
V_{gj}^+	dimensionless weighted mean drift velocity (–)
Wt	bubble duration time (s)
y, D_b	bubble chord length (mm)
$\bar{y}_i, w_i, A_i,$	Gaussian fitting function parameters (–)

Greek letters

σ	surface tension (N/m)
ρ_g	gas density (kg/m^3)
ρ_l	water density (kg/m^3)
ρ_p	nylon fiber density (kg/m^3)
μ_g	gas viscosity (Pa·s)
μ_l	water viscosity (Pa·s)
ε_g	local gas holdup (–)
$\varepsilon_g(r)$	local gas holdup correlation (–)
$\bar{\varepsilon}_g$	cross-section averaging gas holdup (–)
λ	bubble shape factor (–)

Abbreviations

BSD	bubble size distribution
CLD	chord length distribution
IGCC	integrated gasification combined cycle
OMB	opposed multi-burner
PDF	probability distribution function

et al., 2008, 2015), falling film flow (Wang et al., 2013; Yan et al., 2017) and reverse buoyant flow (Gong et al., 2003; Wu et al., 2009; Fu et al., 2011). However, few studies are focused on gas–liquid-solid three-phase flow in the liquid bath. Wu et al. (2009) simulated the distribution of particles in the scrubbing-cooling chamber using a three-dimensional Euler-Lagrange model. Wu et al. (2015) studied the distribution characteristics and movement of glass beads passing through a liquid bath using an Euler-Lagrange method for numerical simulation. In the above studies, spherical particles are used as the experimental materials and only the distribution of the solid phase is studied in the scrubbing-cooling chamber liquid bath, ignoring the influence of the solid phase on gas-liquid two-phase flow. In the actual process, most of the ash particles in the scrubbing-cooling chamber are non-spherical. Compared with spherical particles, the drag coefficient of non-spherical particles is remarkably different (Cui and Grace, 2007). This difference inevitably leads to variations of the particle movement and affects the fluid movement and distribution characteristics. Fiber particles are a kind of typical slender particles, which are flexible, have a certain aspect ratio and have a density close to water. During the operation of the OMB gasifier, numerous fiber particles of certain aspect ratios bridge and deposit on the bubble-breaking plate, which seriously affects the normal operations of the OMB gasifier. Therefore, there are important theoretical and engineering practical values to study the hydrodynamics in the slender particle-containing scrubbing-cooling chamber.

As a composite bubble column, flow regimes in a scrubbing-cooling chamber are different from those of a conventional bubble column. Turning from the outlet of the downcomer, the ash-containing crude coal gas containing flows upward through the annular gap. It is a reverse buoyancy sudden expansion flow in a large diameter annular pipe. Flow regimes in a bubble column are generally classified into bubbly flow, slug flow, churn-

turbulent flow and annular flow (Chen et al., 1994; Shaikh et al., 2007); slug flow mainly exists in bubble columns with small diameters. Gas-liquid two-phase flow in a vertical pipe is similar to that in a bubble column, which can be classified into bubbly flow, cap-bubbly/slug flow, slug flow, churn-turbulent flow and annular flow (Julia et al., 2009). Schlegel et al. (2009) studied the void fraction and flow regime in adiabatic upward two-phase flow in large diameter vertical pipes and reported that when the dimensionless diameter is larger than 40, slug bubbles are no longer sustained due to Taylor instability. Thus, gas-liquid two-phase flow regimes in large diameter vertical pipes can be classified into the following categories: bubbly flow, cap-bubbly flow, churn-turbulent flow and annular flow. When the cross-section averaging void fraction is lower than 0.3, the flow regime belongs to bubbly flow, but cap bubbles have already appeared when the local void fraction is 0.2. Under the influence of cap bubbles, bubbly flow can be classified into undisturbed bubbly flow and agitated bubbly flow (Ohnuki and Akimoto, 2000). However, in a vertical annulus, typical slug bubbles with diameters close to the pipe diameter that occupy almost the whole cross-section will not appear because of the limitations of the annulus structure (Julia and Hibiki, 2011; Julia et al., 2011). In most cases, Taylor bubbles wrapping around the inner tube cannot cover it completely due to the long periphery of the annulus; intermediate flow regimes, cap-bubbly or cap-slug flow, are therefore observed (Julia and Hibiki, 2011; Julia et al., 2011; Paranjape et al., 2011).

Bubble column reactors are widely used in the chemical industry as contact and reaction devices for gas-liquid two-phase flow and gas-liquid-solid three-phase flow. They are used for various large-scale gas-liquid contact and reaction processes for their simple structure, operational ease and low pressure drop (Shah et al., 1982). Bubble size distribution is a key parameter in the simulation and scale-up of a bubble column reactor, it can be used to divide