Experimental Thermal and Fluid Science 74 (2016) 404–410

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

journal homepage: www.elsevier.com/locate/etfs

Experimental studies of the transition velocity in a slurry bubble column at high gas temperature of a helium–water–alumina system

M.W. Abdulrahman

Faculty of Engineering and Applied Science, UOIT, Oshawa, ON L1H 7K4, Canada

ARTICLE INFO

Article history:
Received 7 July 2015
Received in revised form 31 October 2015
Accepted 8 January 2016
Available online 14 January 2016

Keywords:
Slurry bubble columns
Hydrodynamic
Transition velocity
Helium
Flow regimes

ABSTRACT

In this paper, the transition velocity is investigated experimentally for a helium gas at 90 °C injected through a slurry of water at 22 °C and alumina solid particles in a slurry bubble column reactor. This paper examines the effects of superficial gas velocity, static liquid height and solid particles concentration, on the transition velocity of the SBCR. From the experimental work, it is found that the transition velocity between homogeneous and churn turbulent flow regimes, decreases by increasing the static liquid height and/or the solid concentration. It is also found that there is no slug flow regime in the industrial slurry bubble column reactors.

1. Introduction

Slurry bubble column reactors (SBCRs) are systems that contain three-phases; gas, liquid, and solid, in which gaseous bubbles are dispersed through a liquid–solid slurry in a vertical column [18]. These reactors are becoming more competitive due to their inherent advantages and are used in numerous industrial applications. It has been reported that the operating conditions and design as well as the geometry of the column strongly affect the hydrodynamics of the SBCRs [3,4,17].

The hydrodynamics of SBCRs have rigorous dependence on the type of flow regime in the column [4]. The flow regimes in bubble columns can be classified into three types [25]; (1) homogeneous regime (bubbly flow) which is obtained when the superficial gas velocities are low. The sizes and rise velocities of the bubbles in this regime are relatively uniform [5]. (2) Heterogeneous regime (churn-turbulent flow); which is obtained when the gas velocity is increased. In this case, gas bubbles will be more interacted and bubbles coalescence and break up are observed which will lead to a broad distribution of bubble size. (3) Slug flow regime; which is obtained in small diameter columns. In this case, when the gas velocity increases, the bubbles of the gas will coalesce to form slugs with large diameters.

It is very important to detect the regime transition from homogeneous to heterogeneous flow, because there are significant changes in the hydrodynamic behavior of the system when the transition takes place [11]. Because of the importance of flow regimes in the hydrodynamics of the slurry bubble column reactors, lots of studies can be found in the literature regarding this area. A comprehensive study of the published works on the transition superficial gas velocity ($U_{g\text{-}trans}$) from homogeneous to heterogeneous flow regimes has been done by Sarrafi et al. [16], where it can be seen that $U_{g\text{-}trans}$ generally lies in the range of 0.044–0.067 m/s. Shaikh and Al-Dahhan [21] have reviewed most hydrodynamic studies that investigated the flow regime transition in bubble columns. They have summarized the reported experimental studies, along with their operating and design conditions. Thorat and Joshi [22] have reported that the transition gas velocity depends on column dimensions (diameter and dispersion height), sparger design and physical properties of the system.

Most researchers have reported that transition velocities increase with increasing pressure [2,8,9,13,19,26]. Krishna et al. [7] have found that the transition velocity increases by increasing the density of the gas [11].

Mena et al. [10] have investigated the influence of solids concentration on flow regime stability using air, distilled water, and calcium alginate beads. They have found that transition velocity increases with solids loading up to 3 vol.% and then decreases at higher solids loading (>3 vol.%).

Vandu and Krishna [24] and Shaikh and Al-Dahhan [20] observed a decrease in transition velocity when increasing solids concentration, without the maximum as observed by Mena et al. [10]. However, it is worth mentioning that these authors have

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E-mail address: mo-wassef@hotmail.com

http://dx.doi.org/10.1016/j.expthermflusci.2016.01.006
0894-1777/

Nomenclature

C_s	volumetric solid concentration
D_R	diameter of reactor (m)
g	gravitational acceleration (m^2/s)
H	height of static liquid (m)
H_R	height of reactor (m)
j_E	experimental drift flux (m/s)
j_T	theoretical drift flux (m/s)
u	slip speed of bubble (m/s)
u_o	terminal velocity of bubble (m/s)
U_{gs}	superficial velocity of gas (m/s)
$U_{g\text{-}trans}$	transition superficial velocity of gas (m/s)

Greek letters

α_g	gas holdup
$\alpha_{g\text{-}trans}$	transition gas holdup
ΔH	height difference between transducers (m)
ΔP	static pressure drop (Pa)
ρ_g	density of gas (kg/m^3)
ρ_l	density of liquid (kg/m^3)
ρ_{sl}	density of slurry (kg/m^3)
σ	surface tension (N/m)

not studied low solids loading in the range between 0 and 3 vol.% where Mena et al. [10] observed a maximum in transition velocity.

Sarrafi et al. [16] have examined the impact of sparger configurations on transition velocity using reported data on gas holdup and also their own data in the air–water system. They have reported that, for a hole diameter < 1.5 mm, the transition velocity will decrease with increasing the diameter, and for a hole diameter > 1.5 mm, the effect of the hole diameter on the transition velocity is negligible. Sarrafi et al. [16] and Ruzicka et al. [15] found that an increase in liquid static height decreases transition velocity up to 4 m. Beyond this, it almost becomes independent of liquid static height.

The effect of reactor diameter on transition velocity has been studied by different researchers. Some researchers have found that the transition velocity increases by increasing the column diameter [12,23], while others have found that increasing the column diameter reduces the transition velocity [15,27]. Based on their own data and literature data in air–water systems, Sarrafi et al. [16] found that transition velocity increases with an increase in column diameter. However, it becomes independent of column diameter beyond 0.15 m. Thorat and Joshi [22] and Ruzicka et al. [15] have studied the effect of the dimensionless aspect ratio (H_R/D_R) in the air–water systems. They have found that an increase in aspect ratio decreases transition gas holdup.

Since the flow regime transition depends on different parameters, the boundaries between the regimes are not exact and there exist a transition regime where each flow regime can prevail depending on the experimental setup and system used. Thus, regime transitions in bubble columns are still under investigation. From above literature, it can be seen that, most of the previous studies in flow regime transition were carried out for water–air systems. In this paper, the flow regime transition is specified for a high temperature helium gas injected in a mixture of liquid water and alumina solid particles. In the literature, no work has been reported regarding detailed hydrodynamic studies of SBCR with high temperature helium gas. Therefore, this lack motivates the present work, which seeks to fill this gap by investigating experimentally the SBCR using alumina–water slurry at 22 °C and helium gas at 90 °C. The importance of using helium gas lies in being a perfect fluid for transferring heat because of its high specific heat as well as it is inert and safe to use.

2. Experimental work

2.1. Experimental setup

The schematic of the SBCR setup is illustrated in Fig. 1. All experiments were conducted in a stainless steel column with 21.6 cm inner diameter and 91.5 cm height. The diameter of the reactor was chosen to be larger than 15 cm to minimize its effect on hydrodynamic studies [1]. The reactor consisted of four sections provided with flanges for easy construction and flexibility and also for easy installation and removal for cleaning purposes. The reactor was provided with two Jerguson site-windows, located in the middle of the second section from the bottom of the reactor. These windows were placed in opposite directions to allow the light to penetrate through one of the windows in order to enable a clear vision for the bubbles behavior under a given operating condition. A ball valve was installed at the bottom of the column to drain the slurry and clean the column. The column wall was thermally insulated to reduce heat losses from the column wall [1].

There are four pressure transducers, provided by OMEGA (PX209-030GI), mounted to pressure taps at different locations on the reactor, which allow the measurement of the hydrostatic pressure head at any level in the reactor. The locations of the pressure transducers are 21 cm, 42.5 cm, 61.6 cm and 80.6 cm above the bottom of the column. The four transducers could measure pressures up to 207 kPa and their operating temperature range is from −54 °C to 121 °C. The accuracy of the pressure transducer is 0.25% full scale (including linearity, hysteresis and repeatability) and the output signal is electrical current (4–20 mA) [1].

Six quick disconnect thermocouples of type K with removable standard size connectors, were arranged at different distances inside the column to measure the temperature along the column height. These distances are, 15.2 cm, 25.4 cm, 37.5 cm, 47.6 cm, 61.6 cm and 80.6 cm, from the bottom of the column. The special limits of error of a thermocouple is 1.1 °C or 0.4% (whichever is greater) [1].

Helium gas is introduced from a supply vessel into the bottom of the column through a six-arm spider-type gas distributor made from stainless steel. Each arm has 4 orifices of 3 mm diameter on each side and on the bottom, totaling 12 orifices. There are no openings on the top of the arms so that no solid particles could block the orifice. The maximum height of the sparger from the bottom of the column is about 10.8 cm (refer to Fig. 2). The orifice diameter of the gas distributer was designed to be 3 mm, because the gas sparger has a minimal effect on the bubble sizes and gas holdup if the orifice diameters are larger than 1.5 mm [1].

The helium volumetric flow rate is measured using a digital flow meter of type (FMA-1612A-I) that is connected to a pressure regulator of type OMEGA (PRG501-120) to control the flow rate. The maximum flow and accuracy of the flow meter is 500 SLM and ±(0.8% of reading + 0.2% of full scale) respectively. A stainless steel helical tube inside an electrical furnace was installed in place after the flow meter to heat the helium gas to 90 °C before entering the reactor column. The outside diameter of the tube is 1.3 cm and the wall thickness is 1.6 mm. The coil diameter, length and pitch