Hydrodynamics of a bubble column with phase change

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HIGHLIGHTS

- Bubble column with phase change has been studied using a vapor-water system.
- Hydrodynamics with phase change are very different from that without phase change.
- Axial profile of temperature results in complex condensation and vaporization behaviors.
- Gas holdup has a U-shape axial profile in bubble column with phase change.
- Phase change leads to a much wider bubble size distribution.

ARTICLE INFO

ABSTRACT

The bubble column reactor with phase change are used in some important chemical processes, but its hydrodynamics has not been well studied. In this work, the hydrodynamic behaviors of a bubble column with phase change were experimentally studied using a vapor-water system. The axial profiles of liquid temperature, total and local gas holdups, and bubbles size distribution were measured. The results showed that the hydrodynamics with phase change were very different from that without phase change. The temperature was lower than the liquid boiling point in the bottom region, and this difference decreased with increasing axial height. With phase change, the gas holdup showed a "U" shaped axial profile, while without phase change it showed a flat axial profile. In addition, phase change led to a much wider bubble size distribution. The results were analyzed based on the heat and mass transfer between the gas and liquid phases. These experimental data were valuable for further development of a mathematical model to describe the complex hydrodynamics in a bubble column with phase change.

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1. Introduction

Phase change is an important phenomenon in some industrial bubble column reactors operated at high temperature and pressure (Khadilkar et al., 1999). Typical examples are the synthesis of biodiesel (Joelianingsih et al., 2008), synthesis of poly-oxymethylene dimethyl ethers (PODE$_n$), and some hydrogenation reactions (Jaguste and Bhatia, 1991; Lavopa and Satterfield, 1988; Khadilkar et al., 1999).

The phase change is involved in the bubble column mainly for two purposes. In one case, the reactants or products were evaporated to stir the liquid phase and homogeneously suspend the solid catalysts. For example, the process of synthesis of biodiesel from methanol and waste oil (Joelianingsih et al., 2008) is companied with phase change of methanol. The methanol vapor enhances the contact and mass transfer between methanol and waste oil. Recently, our group (Zheng et al., 2013) studied the production of polyoxymethylene dimethyl ethers (PODE$_n$), a green diesel fuel additive, from dimethoxymethane and paraformaldehyde in a stirred autoclave reactor. A pilot plant of 10,000 t/a has been setup using a slurry bubble column. In this process, the dimethoxymethane fed in the reactor vaporized because the reactor was operated near the boiling point of dimethoxymethane. The vapor of dimethoxymethane was used as the lifting gas to intensify the mass transfer and suspend the solid catalysts.

In the other case, the liquid vaporization is used for temperature control in a system where the reaction heat is very large. One example is the process of cumyl hydroperoxide decomposition in a three-phase fluidized bed reactor (Huang et al., 2001), where the vaporization of product acetone is used to remove the reaction heat to control the reaction temperature. Another example is the process of benzene hydrogenation where the vaporization of benzene and cyclohexane is used to remove the reaction heat (Cheng and Yuan, 2002).

Some works have been reported on the reactors with phase change, but few have focused on the bubble column. Early works

mainly focused on the reaction thermodynamics and kinetics, including the evaluation of catalyst efficiency, optimization of operating condition, and scale-up of the reactor. In recent years, researchers began to study the hydrodynamics of reactors with phase change. Kirillov and Koptyug (2005) studied the multiplicity of steady-state regimes, hysteresis phenomena, and the effect of both liquid flow rate and particle size on the appearance of critical phenomena in a trickle bed with phase change under conditions of exothermal hydrogenation reaction. Gulawani et al. (2009) studied the flow pattern and heat transfer in direct contact condensation in a rectangular gas-liquid jet reactor and studied the development of temperature profiles by CFD simulations. Li et al. (2010) studied the influence of volumetric flow change on the gas holdup profile and bubble size in a gas-solid fluidized bed by CFD simulations. They found that the change in volumetric flow had a significant effect on the hydrodynamic behaviors. The change in volumetric flow could be caused by variation in the total molar flow due to reaction, change of phase, utilization of membranes, and changes in temperature and pressure. However, little work has been done on the bubble column with phase change. Considering that the bubble column is one of the most important reactors (Wang et al., 2007) and many processes involve phase change phenomena, it is necessary to study the hydrodynamics in a bubble column with phase change to guide the reactor design and optimum operation.

In this paper, the hydrodynamics of a bubble column with a vapor-water system was studied. Deionized water heated to near its boiling point was used as the liquid phase. The superheated vapor was used as the gas phase and was injected from the bottom of reactor. Very different hydrodynamic behaviors were found compared with the gas-liquid system without phase change.

2. Experimental

2.1. Experimental setup

The schematic of the experimental apparatus is shown in Fig. 1. The column was 50 mm i.d. and 1800 mm high, and was made of glass to withstand high temperature and facilitate observation. The gas distributor was a sintered porous plate with pore size of 25 µm. A constant mass flow pump was used to control the flow rate of water to the vaporizer. Then the vapor flow of 125 °C was produced and was jetted from bottom of the bubble column. The thermodynamic properties of water-vapor system was listed in

Fig. 1. Schematic of the experimental apparatus.

Table 1
Liquid and vapor properties at 100 °C and 101 kPa.

	Density (kg/m^3)	Viscosity (10^{-5} Pa s)	Surface tension (10^{-3} N/m)
Water	958.4	28.4	58.8
Vapor	0.59	1.23	–

Table 2
Superficial velocity of the vapor flow at 125 °C ($\rho_G = 0.59$ kg/m^3 in this work).

Mass flow, g/min	Superficial velocity, m/s
15	0.054
20	0.072
25	0.090
30	0.108
35	0.126
40	0.144
45	0.162

Table 1 and the corresponding superficial gas velocities were listed in Table 2. The liquid in the column was deionized water with an expanded height of 1600 mm adjusted by an overflow pipe. The reactor was operated at ambient pressure. A heating rod of 20 mm in diameter was installed in the center of the column to preheat the water. The reactor wall was wrapped with insulating layer to reduce heat loss. For each experiment, when the deionized water was heated to 100 °C, the heating rod was turned off and the superheated vapor of 125 °C was jetted from bottom of the bubble column to produce vapor bubbles in water.
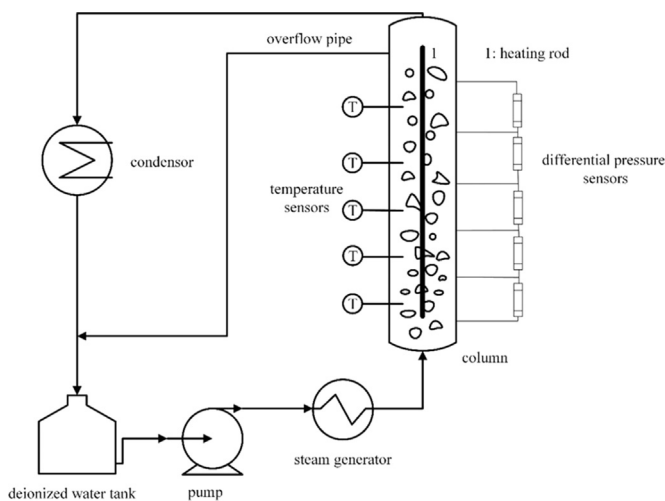
2.2. Measuring method

Five temperature sensors of platinum resistance were distributed along the axial direction to measure the liquid temperature. The wet-wet differential pressure sensors used in this work had a response time of 0.1 s and sensitivity of $\pm 0.1\%$. For each measurement, the sampling time was 30 s and the sampling frequency was 100 Hz. The reducibility error of the results was 0.54%. The profile of the gas holdup was measured by the differential pressure method based on the following equation:

$$\Delta P = \rho_l gh - \rho_T gh(1 - \alpha_g) \tag{1}$$

where ρ_l and ρ_T are the density of water at ambient temperature and operating temperature, respectively. Both densities are at ambient pressure.

The bubble size distribution was measured by a digital camera, as shown in Fig. 2. For each condition, at least 1000 bubbles were analyzed to get a sufficiently representative bubble size distribution. High-quality images were obtained by illuminating the flow with diffused uniform back white light. The bubbles in the picture were processed with the image processing software Image Pro-Plus, which has been commonly used in literatures to get the bubble size distribution (Buwa and Ranade, 2002, 2004; Majumder et al., 2006). The bubble size was evaluated with the cross-sectional area A_i using the method developed by Schafer et al. (2002). In this method, the bubble size was estimated based on the cross-sectional area A_i of all selected non-overlapping bubbles. The diameters of spherical bubbles were calculated with the correlation of $d_i = \sqrt{4A_i/\pi}$. This method was accurate for small bubbles, but had a larger uncertainty for large bubbles due to their severe deformation. Schafer et al. (2002) found that for large ellipsoid bubbles with aspect ratio of 2, the average bubble size was underestimated by about 6%. In this work, few bubbles deformed so seriously and the calculation error was less than 6%.