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Bubbles in curved tube flows – An experimental study

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ABSTRACT

The heat transfer of boiling flows in helically-coiled tubes has significant relation with the bubble dynamics in the curved flows. To understand the bubble dynamics in curved flows, we experimentally study air bubbles in water flows in a coiled tube, which is approximately considered as a toroidal tube. The torus is perpendicular to the ground. Air bubbles are generated by injecting constant air flow at varied locations of the torus. Focus is put on the relationship of the bubble departure and traveling path with the water flow and injection location. The force analysis includes the gravitational force, the drag forces by the main and secondary flows, and the centrifugal force. Injection at the outer side of the torus shows higher bubble departure rate than the inner side, which is caused by the higher drag force of main flow at the outer side. The displacement of bubble traveling path between the inner and outer sides is mainly affected by the gravitational force for slow curved flows, and is dominated by the centrifugal force for fast curved flows.

1. Introduction

Due to the compactness in volume and high efficiency in heat transfer, coiled tube flows have been widely in the heat exchangers in food processes, air conditioning and cryogenic systems and nuclear reactors [1–5]. Vashisth et al. [6] provided an overview on the industrial applications of the coiled tube flows.

A number of studies have been conducted to investigate boiling flows in helically coiled tubes [7–14]. In 1968, Owhadi et al. [7] experimentally investigated the forced convective boiling of water flows in helically-coiled tubes. It was postulated that the secondary flow in the vapor core affects the liquid flow on the tube wall. Naphon and Wongwises [9] provided a literature review on the flow and heat transfer characteristics in curved tubes, which includes boiling flows in helically-coiled tubes. Many studies focused on the trends of experimental parameters such as mass flux affecting heat transfer coefficient and critical heat flux (CHF) [10–13]. Additionally, a number of correlations have been proposed for predicting the heat transfer coefficient [10,11,14].

Bubble dynamics has significant effects on the heat transfer of boiling flows. This has been investigated for flow boiling in straight channels [15–18] by relating the observed bubble characteristics to the applied thermal conditions or to the measured heat transfer performance. Previous studies [7,10–13] have revealed significant local characteristics of heat transfer for flow boiling in coiled tubes, for which explanations were attempted by discussing the bubble dynamics. However, very little experimental work has been reported regarding the bubble dynamics in coiled tubes. The bubble dynamics in coiled tubes should be significantly different from straight channels due to the complex fluid dynamics of curved flows [19,20]. If the coil is horizontally placed (i.e. the coil axis is parallel to the ground), gravity plays a major role in affecting the bubble dynamics.

Most previous studies on bubble dynamics have been focusing the formation and behaviors of air bubbles either in straight flows or in stationary fluids [21–27]. For example, Oguz and Prosperetti [22] studied the growth and departure of bubbles from a needle submerged in both quiescent fluid and flowing fluid. Davidson et al. [23] studied the formation of air bubbles when air is blown steadily through an orifice submerged in a quiescent viscous liquid. Tomiyama et al. [24] measured the trajectories of single bubbles in shear flows of glycerol-water solution to evaluate the transverse lift force acting on a bubble. Kulkarni and Joshi [25] provided a review on the formation of gas bubbles and their subsequent rise due to buoyancy. Ghaemi et al. [27] investigated the effect of gas-injector location on bubble formation in straight liquid cross flows. None of the studies are related to the curved flows in coiled tubes.

The objective of the present work is to investigate the bubble characteristics in coiled tube flows. As discussed above, the injection of non-condensable gas has been a commonly used method

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for studying bubble dynamics in different types of flows. The results of non-condensable bubbles are useful for understanding the behaviors of vapor bubbles in actual boiling flows. In the present work, air bubbles are formed by injecting air into water flows through a thin nozzle.

2. Experimental methodology

The experimental methodology is illustrated in Fig. 1*a*. Curved flows are formed by pumping constant water flows through a coiled transparent PVC tube. The tube is coiled into two consecutive rings, which are placed such that the axis of the rings is parallel to the ground. There is extra straight tube before and after the two rings to make smooth tangential transitions between the straight and curved flows. The first (upstream) ring is for the curved flows to develop, while the second one is the test section. Supplied by a syringe pump, constant air flow is injected into the second ring of the coiled tube by a nozzle made of a thin stainless steel tube, which penetrates the PVC tube wall. Viewing in the A-A direction (see Fig. 1*a*), a high speed camera (Phantom Miro M310) is used to record the flows inside the second ring of the coiled tube. Details of the experimental method and conditions are described below.

Transparent PVC tube with an inner diameter a=8 mm is coiled into two consecutive rings with the coil radius R=65 mm. As shown by Fig. 1*b*, R is the distance between the coil center and the tube center. The bending can be quantitatively evaluated by the ratio of the tube diameter to the coil diameter, $a/(2R)$=0.06 for the present work. The flow rate of water is varied by adjusting the pump and measured by the flow meter. As a result, the mean velocity of the water flow, denoted by $\overline{W}$, ranges from 0.13 to 1.13 m/s. The Reynolds number of the flow is defined as

$$\mathrm{Re}_m = \frac{\overline{W}a}{\upsilon} \tag{1}$$

where υ is the kinematic viscosity of water. Hence, Re_m ranges from 1040 to 9040.

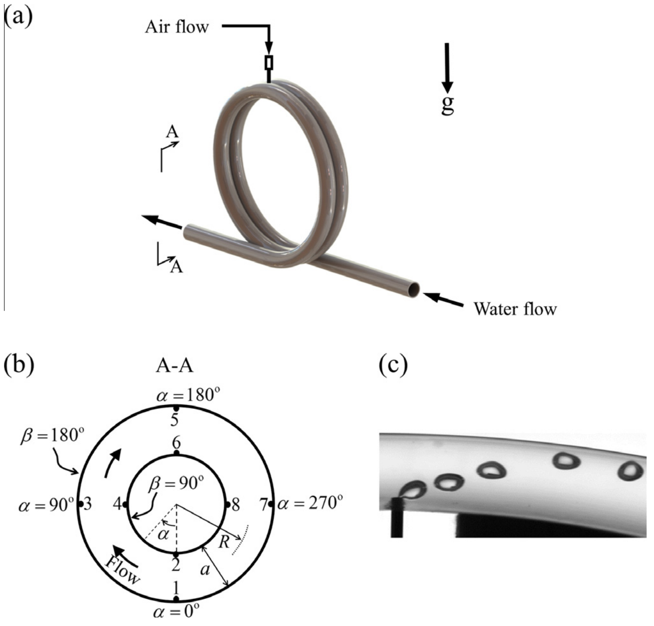

Fig. 1. (a) Water flow is forced through the PVC tube coiled into two rings, and the air flow is supplied by a syringe pump. High speed camera views in the A-A direction; (b) The second ring is considered a toroidal tube with the eight locations for air injection specified by α and β; (c) Bubbles formed when air is injected at location #6.

It has been observed that curved flows are more stable than straight flows in terms of the transition from the laminar regime to the turbulent regime, and the critical value of Re_m is larger than that for the straight flows by a factor or two [28]. The transition of flow regime has been found to be dependent on the ratio $a/(2R)$ [29,30]. For $a/(2R)$=0.06 and $Re_m \leqslant 9040$, the flows tested in the present work are not turbulent.

The upstream ring of the coil is used as the entrance region for the curved flow to develop, and the flow inside the downstream ring is tested. In the present work $2\pi R/a{\sim}50$, which should be sufficient for straight tube flows to fully develop [31]. Here we assume that this is also sufficient for the full development of the curved flows studied in the present work. In other words, the curved flows in the second ring are fully developed flows.

Since the two rings of the coiled tube are in contact without gap (see Fig. 1*a*), the pitch of the coil is the outer diameter of the tube, 12 mm, which is much less than $2R$. Hence, the tested ring of the coiled tube can be considered as a torus, or a toroidal tube. As shown by Fig. 1*b*, the torus is placed vertically and perpendicular to the ground. Observed in the tests, the water flow inside the torus is clockwise. Following the flow direction, an angle α is used to define the angular position, with α=0° and 360° set at the bottom of the torus. The cross section of the coiled tube approximately remains circular, and another angle β is used to represent the angular position on the tube cross section. For the inner side of the torus, β=0°, and for the outer side of the torus, β=180°.

Bubbles are generated by injecting air with constant flow rates into the water flow. The flow rate of the air, $\dot{\mathrm{V}}$, is varied from 0.2 to 1 ml/s. The air flow is supplied by a syringe pump connected to a nozzle made of a thin stainless steel tube, which has an inner dimeter of 0.7 mm and an outer diameter 1.1 mm. As shown by Fig. 1*c*, the nozzle penetrates through the PVC tube wall with the nozzle tip slightly beyond the inner wall of the tube by ~0.1 mm. The penetration is maintained constant for all the tests with varied injection locations. Air injection is done at eight locations of the torus specified by α and β, and the eight locations are numbered in Fig. 1*b*. Locations #1, 3, 5, 7 have $\beta = 180°$ and $\alpha = 0°, 90°, 180°, 270$, respectively, while locations #2, 4, 6, 8 have $\beta = 0°$ and $\alpha = 0°, 90°, 180°, 270°$, respectively. In Fig. 1*c*, air is injected at location #6.

The bubbles in the water flows are recorded using the high speed camera set at 1200 frames per second. As shown by Fig. 1*c*, the high speed images are used to observe the departure of bubbles from the nozzle and the trajectory of the bubbles in the flow. The high speed videos can also be used to measure the number of bubbles formed per second, which is referred to as bubble departure rate and denoted by f. All the bubbles show deformation and differ from the spherical shape. The bubble size can be quantified using an equivalent diameter, d, which can be calculated using

$$\frac{\pi}{6}d^3 = \frac{\dot{V}}{f} \tag{2}$$

Here the injected air has been assumed incompressible for the following reason. Both the capillary pressure of the bubble and the pressure drop through the torus are in the order of magnitude $O(10^2\ \mathrm{Pa})$, which is only ~0.1% of the atmosphere pressure.

3. Force analysis

Fig. 1*c* shows that bubbles are formed from the continuous flow of injected air. The bubble still attached to the nozzle shows being dragged in the direction of the main flow. It is understandable that the forces on the bubble prior to detaching from the nozzle affect the bubble generation. After detaching from the nozzle, the forces on the free bubbles would affect their travelling paths.