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Experimental study on the characteristics of air–water two-phase flow in vertical helical rectangular channel

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ABSTRACT

Experimental investigations on the characteristics of air–water two-phase flow in the vertical helical rectangular channel are performed using the high speed flow visualization. The flow pattern map and the transition in the helical rectangular channel are presented. The flow pattern evolution in different positions of the helical rectangular channel is illustrated. The discussion on the coalescence of the bubble and slug is presented. The slug velocity, slug length distribution, liquid slug frequency, falling liquid film velocity and falling film thickness along the slug are investigated. The dimensionless liquid film thickness of the annular flow on the outer side of the channel is measured using the digital image processing algorithm.

Introduction

Helical channels are of great importance in many industrial applications, such as power engineering, heat recovery processes, air conditioning and refrigeration systems, chemical reactors, nuclear reactors, steam generators and other heat transfer equipment (Bolinder and Sunden, 1995; Awwad et al., 1997; Sasmito et al., 2012). Two-phase flow in the helical channel is much more complex in nature than that in the straight pipes. When the air–water flows through the helical channel, the heavier fluid is shifted to the outer side of the channel due to the dominant effect of centrifugal force, while the gas flows towards the inner side of the channel (Biswas and Das, 2008).

Two-phase flow characteristics in helically coiled tubes are more complex and important for engineering applications. Some numerical works have been reported on the flow characteristics. Vashisth and Nigam (2009) presented the local variables and interfacial phenomena as the two-phase flow through the helical pipe. Jayakumar et al. (2010) presented the hydraulic characteristics of the air–water two-phase flow in the helical pipes. CFD analysis was carried out with varying configuration parameters and the influence on thermal hydraulic characteristics of the two-phase flow was brought out. Xia et al. (2014) investigated the flow characteristics and pressure drop in helical rectangular channel, the development of the liquid distribution and pressure gradient along the helical rectangular channels was presented.

Compared with the limited numerical investigations of two-phase flow characteristics through helical tubes, experimental works regarding the two-phase flow characteristics are also insufficient in the open literatures. Kumar et al. (2009) investigated the effect of various dynamic and geometric parameters on mass transfer coefficients in helically coiled flow systems. Murai et al. (2005, 2006) performed the two-phase flow in the helical pipe and the effects of centrifugal acceleration on the flow structure distribution were elucidated. Vashisth and Nigam (2008) carried out experimental investigation on the void fraction and flow patterns in coiled flow inverter, the flow pattern chart showing smooth-stratified, stratified-wavy, slug flow, plug flow, wavy flow and churn flow regimes were presented. Chen and Guo (1999) investigated the oil–air–water three-phase flow in helically coiled tubes, whereby the flow patterns and pressure drop in the test channel were obtained.

The two-phase flow structure in the screw channel of single screw expander prototype is one of the most important factors that affect the efficiency of the expander (Wang et al., 2011). The previous researches mainly focused on the processing and the performance of the prototype, and the two-phase flow structure in the screw channel remains an issue for further studies (Liu et al., 2014). To our knowledge, no attempt has been made to investigate the flow characteristics in helical rectangular channel. This paper aims to explore the fine features of two-phase flow in helical

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rectangular channel. The findings in the present paper can give much insight into the physics of the problem in single screw expander prototype.

Experimental apparatus

Characteristics of helical rectangular channel

The schematic of the vertical helical rectangular channel with its main geometrical parameters is presented in Fig. 1. The cross-sectional geometry of the channel ($a \times b$) is considered as 30 mm × 16 mm. The pitch circle diameter (D) is taken as 155 mm. The pitch (H) of the helical rectangular channel in this paper is given as 329.7 mm. The side of the channel wall which is nearest to the coil axis is termed inner side and the outmost side is termed as outer side. The dimensionless parameters curvature and torsion are defined as $\delta = d/D$, $\lambda = H/\pi D$ (d is the hydraulic diameter of rectangle cross-section). The centrifugal acceleration is defined as U^2/R. The Reynolds number $Re = \rho dU/\mu$. The Dean number is used to characterize the flow in helical pipe. That is defined as $De = Re\delta^{0.5}$ (Xia and Liu, 2014).

Experimental apparatus

Fig. 2 shows the outline of the experimental loop used in the present study. It consists of air supply system, water supply system, test section, data acquisition system, flow measuring apparatus, flow controlling system and high speed camera system. Air and water are taken as the working fluids. Water is circulated in the loop from a storage tank. Air is supplied by an air-compressor and then flows through the air measuring station. Their flow rates are adjusted by controlling valves. The air flow rate is measured by a vortex flow meter with an accuracy of ±1.0%. The water flow rate is measured by an electromagnetic flow meter with an accuracy of ±0.5%. These two fluids can be mixed in the mixing chamber. The distance from the mixing chamber to the test channel is about 1.2 m. The entrance and exit of the test channel are connected with the variable-section transition channel, which is made for the connection of the test channel with the flow loop. The length of the variable-section transition channel is approximately 100 mm. The flow patterns are distinguished and recorded by high speed camera using the backlight imaging tomography. The frame rate of Motionpro X4 high-speed camera can be selected in the range of 30–5000 fps. The pressure measurement probes are fixed at the 30° turn and 300° turn of test channel and it is statistical to measure the pressure drop and pressure fluctuation in helical rectangular channel.

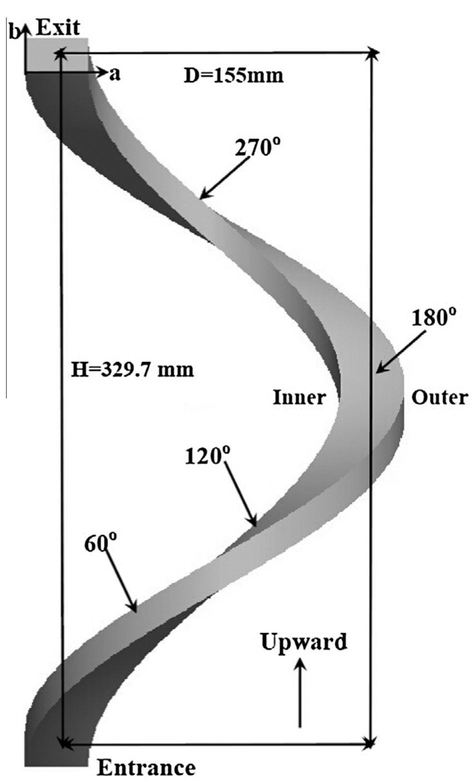

Fig. 1. Schematic of the helical rectangular channel with its main geometrical parameter and longitudinal view of the backlight imaging unit.

Backlight imaging

Fig. 1 shows a longitudinal view of the visualization unit employed in the study. The curvature of the helical rectangular channel makes it difficult to measure the flow feature of the air–water flow. In order to show the effect of the centrifugal acceleration on the two-phase flow pattern evolution characteristics, the visualized flow patterns in the test channel is presented at the four positions. The position of each lamp is adjusted carefully so that the brightness distributions of all projected images become almost uniform. The backlight image at an arbitrary angle is obtained in the same relative angle between the camera and the direction of the light source.

Results and discussion

Flow patterns and their transition mechanisms

With the aid of flow visualization, appearance of main flow patterns at the 180° of the vertical helical rectangular channel is presented in Fig. 3. Six flow patterns are identified according to previous literature (Zeguai et al., 2013).

(1) Bubbly flow: This flow pattern takes place at low gas superficial velocities and high liquid superficial velocities. In bubbly flow air is distributed as discrete bubbles in continuous water. The bubble has a spherical shape or may be deformed with a bubble length less than the tube diameter. The effect of the centrifugal acceleration on the bubbles distribution is clearly presented in Fig. 3. The liquid is subjected to a larger centrifugal force which causes the water to move along the outer side of the channel, while the bubbles flow along the inner side of the channel.
(2) Intermittent flow: This flow pattern appears in the flow region between the bubbly flow and the annular flow.
(3) Annular flow: This flow pattern is defined when the air occupies the core of the pipe and liquid film is formed on the pipe wall which is dragged upward by air due to the interface friction. The liquid film is broken and turns into small droplets due to interaction of phases in high air flow rate. These small droplets are shifted to the outer side of the channel by the effect of larger centrifugal acceleration. The liquid thickness on the outer is much higher than the inner side.

A map of two-phase flow patterns at the 180° of the vertical helical rectangular channel is depicted in Fig. 4. A detailed description is needed because for flow characteristics there is a change in the different position. Generally, the flow pattern map is similar to that of a vertical straight tube; however, some differences are identified. The transition between intermittent and annular flow occurs