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A mechanistic analysis of shell-side two-phase flow in an idealised in-line tube bundle

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ABSTRACT

This paper reports on an experimental study of air–water mixtures flowing through an idealised shell and tube, in-line heat exchanger. Void fraction measurements are reported for the minimum gaps between the tubes at near atmospheric conditions. The pressure distributions around some tubes are also reported. These data are combined with data available in the open literature to investigate pressure drop and void fraction prediction methods for these heat exchangers. The data are shown to be flow pattern dependent. Criteria for flow pattern boundaries are deduced from previously published flow maps. Void fraction data in the maximum gap between the tubes are shown to be compatible with the drift flux model and to be different in magnitude to the minimum gap values, which are shown to result from acceleration phenomena in the gaps between the tubes. The pressure drop data are analysed through a one-dimensional model that incorporates separation and re-attachment phenomena. The frictional pressure drop is shown to depend on a liquid layer located on the upper portion of the tubes at low gas velocity and on acceleration effects at high gas velocity.

1. Introduction

Shell and tube heat exchangers are commonly used in the process industry to boil liquids. The design of these units is frequently based on modelling the shell-side fluid flow through a one-dimensional formulation of the mass, momentum and energy equations. This approach requires empirical inputs for the void fraction and the frictional pressure drop. Several investigators have proposed void fraction correlations, e.g. Schrage et al. (1988), Dowlati et al. (1990) and Feenstra et al. (2000), while Ishihara et al. (1980), Xu et al. (1998), and Simovic et al. (2007) have proposed methods for frictional pressure drop.

The void fraction correlation of Schrage et al. (1988) was derived from air–water data obtained from an in-line tube bundle containing tubes 7.94 mm in diameter on a pitch to diameter ratio of 1.3. The void fraction was measured using a quick closing valve technique that produced the mean void fraction for the tube bundle. The Dowlati et al. (1990) void fraction correlation was derived from air–water data obtained from in-line tube bundles containing tubes 12.7 and 19.05 mm in diameter on pitch to diameter ratios of 1.75 and 1.3 respectively. Further data were obtained under similar circumstances for staggered bundles, Dowlati et al. (1992a), that showed that tube bundle layout had an insignificant effect. Their method was tested against R113 data sets, Dowlati et al. (1996), with the correlation constants found to be fluid property dependent. These data were based on gamma-ray densitometer measurements. The gamma-ray beam was spread across a tube pitch so that row average void fraction measurements were assumed to have been made. However, since some of the flow was sheltering in the gap between the tubes, maximum gap values may have been obtained. The Feenstra et al. (2000) void fraction correlation was derived from R11 data obtained just upstream of staggered tube bundles containing tubes 6.35 mm and 6.17 mm in diameter on pitch to diameter ratios of 1.44 and 1.48 respectively. It was also tested against air–water and R113 data sets, Dowlati et al. (1990, 1992a, 1996), and is therefore probably the most general of the methods available. Sadikin et al. (2010) obtained void fraction and pressure drop measurements from a tube bundle containing tubes 38 mm in diameter using air–water flows at near atmospheric conditions. The pitch to diameter ratio of the in-line tube bundle was 1.32. The void fraction measurements were obtained from gamma-ray measurements in the maximum gap between the tubes and were therefore local values.

Ishihara et al. (1980) produced a two-phase multiplier correlation of the Chisholm ‘C’ type, Chisholm (1983), that was derived from a data base containing several fluids and tube bundles, all of which contained tubes with diameters less than 20 mm. The ‘*C*’ value was taken to be constant. The method has been found to be reasonable provided the mass flux was large, Dowlati et al. (1990). Xu et al. (1998) carried out tests on a cross-flow heat exchanger with tubes 9.79 mm in diameter on a pitch to diameter

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ratio of 1.28 using air–water mixtures near atmospheric conditions. They also produced a Chisholm 'C' type correlation for two-phase multiplier, Chisholm (1983). However, they correlated their 'C' value as a function of the gas and liquid flow rates. Simovic et al. (2007) used an approximate single-phase method to determine the wall force on the two-phase flow. They used the void fraction to split the tube bundle into a liquid-only and a gas-only section and applied a single-phase method to each. This effectively translates to a frictional pressure drop method that does not include a two-phase friction interaction term.

Flow pattern maps have been reported by several investigators. Grant and Chisholm (1979) reported air–water flow patterns for a segmentally-baffled heat exchanger. They presented their data on a flow map with axes scaled to hopefully include other fluids. Kondo and Nakajima (1980) tested several heat-exchanger configurations with air–water mixtures and found that the flow regime boundaries depended only on the superficial gas velocity, but the flow rates they used were small. Ulbrich and Mewes (1994) pointed out that the range of data used in the formation of the map of Grant and Chisholm (1979) was limited and that only air–water data had been used, so that the ordinate system had not been verified for other fluids. Their flow map used a larger range of air–water data taken from a tube bundle with tubes 20 mm in diameter on a pitch to diameter ratio of 1.5. Grant and Chisholm (1979) and Ulbrich and Mewes (1994) used visual observations to determine their flow maps. Noghrehkar et al. (1999) used a void probe method to determine their map and produced air–water data covering a still larger range for staggered and in-line tube bundles containing tubes 12.7 mm in diameter on a 1.47 pitch to diameter ratio. They reported that the bubbly–intermittent boundary of Ulbrich and Mewes (1994) could be in error at large water superficial velocities because visual observations at the front of the heat exchanger did not represent what was going on in its depth. Aprin et al. (2007) also used a voidage probe method. They obtained a flow map for boiling pentane, iso-butane and propane at various pressures. They concluded that the transition boundaries in flow maps for boiling fluids are significantly lower than for air–water systems. Thus, shell-side flows are known to occupy one of three main flow patterns, bubbly, intermittent and annular. There is little consistency in the available flow maps. Maps required for any application would need to have been obtained at similar conditions.

The void fraction and pressure drop measurements obtained by these investigators produced bundle average or pitch average values that were used in the formulation of the various correlations. These correlations were formulated without any reference to the flow phenomena that occurred in the passages between the tubes. For example, shell-side, two-phase multiplier correlations are extensively used. They are based on an assumed similarity with pipe frictional pressure drops. However, shell-side pressure drop is mechanistically different. Pipe flow pressure drops are due to wall friction whereas shell-side pressure drops are due to flow separation and re-attachment phenomena.

In this study, the experimental work of Sadikin et al. (2010) is expanded. Void fraction measurements at two further locations are reported. These additional void fraction measurements were taken in the same test facility and at the same nominal conditions to allow comparison and compatibility. The void fraction variation with position is demonstrated. Additionally, two-phase pressure distributions around some tubes are reported. These distributions, along with previously reported pressure drops, Sadikin et al. (2010), are used in conjunction with the local void fraction measurements to deduce a mechanistic model of the flow on the shell side. This model is flow pattern dependent. Flow pattern transition criteria are deduced.

2. Experimental apparatus

The flow loop used to obtain the experimental data is illustrated in Fig. 1. Water was taken from the supply tanks and driven by a positive displacement pump to either the test section or back to the supply tank via the recirculation line. The water flow rate was set to the required level by adjusting the valve placed in the recirculation line. Water entered the test section after passing through one of four parallel flow measurement nozzles. Each nozzle had a different throat diameter, allowing a wide range of flows to be measured. The accuracy of the water flow measurements was ±1.0%.

Compressed air flowed from the supply vessel to one of three magnetically coupled measurement rotameters, of which only two were used. A gate valve downstream of each rotameter allowed the air flow rate to be set to the required value. The two parallel flow meters used had ranges of 0–0.0039 and 0–0.034 kg/s. The flow meters were calibrated at the line pressure and were accurate to ±1.6% of reading.

The air and water flows were mixed before passing through the test section and into the air–water separator, where the air was discharged to the atmosphere and the water was returned to the supply tanks.

The test section consisted of five sections, a bubble generator, a convergent section, a settling length, a tube bundle and a second convergent section, as shown in Fig. 2. These parts were fabricated from Perspex sheet that was 12 mm thick and Perspex rod that was 38 mm in diameter. Sheets and rods were joined together by bolts and groves to provide a transparent view of the flow.

The bubble generator contained two pieces of sintered metal porous tube that were 110 mm long, 50.0 mm in outside diameter and had an effective pore size of 206 μm. They were placed in a rectangular Perspex box that was 224 mm in height, 100 mm in depth and 100 mm in width. Water entered the Perspex box from below. Air was fed to the porous tubes from both sides. This produced a reasonably even two-phase flow that passed through the first convergent section and the 244 mm settling length before entering the tube bundle. A further convergent section allowed the test section to be connected to the air–water separator.

An idealised tube bundle was constructed to try to minimise inter-column effects. It contained 10 rows of tubes with an outside diameter of 38.0 mm, incorporating one full central column of tubes and two columns of half tubes placed on the walls to simulate the presence of other columns. The tubes were 54.0 mm in length, with 50.0 mm exposed to the fluid. The remaining 4.0 mm was inserted into 2 mm grooves in the front and back walls to fix the tubes into position. The tubes were arranged in an in-line configuration with a pitch to diameter ratio of 1.32. The central tube in rows 3 and 10 could be rotated and contained a pressure tap that was 1 mm in diameter and normal to the surface, Fig. 2. This allowed the difference between the row approach pressure and the surface pressure be measured at any angle of rotation. The test section was also assembled with the tube bundle rotated through 180° to that shown. For this arrangement tubes 3 and 10 became tubes 8 and 1 respectively. This arrangement was tested at similar conditions to the first in a separate test series.

The fluid pressure was measured at the pressure tap located between rows two and three of the heat exchanger, Fig. 2. A gauge pressure transmitter accurate to 0.25% of range was used. A further two pairs of pressure taps were available, one pair for each rotating tube. Each pair had one pressure tap located mid-way between the row containing the rotating tube and the row upstream of it. The other was located on the tube surface, mid-way along its length. These allowed the pressure differences between a fixed location and the tube surface to be measured. The tube was rotated through