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An Experimental Study of The Effects of The Mixing Vane on Air-Water Mixed Flow

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ABSTRACT

The effects of a mixing vane on air-water mixed flow have been experimentally studied in this work, to investigate the basic mechanisms that the mixing vane affects critical heat flux (CHF). Experiment was performed for various flow rates focusing on bubbly flow and annular flow patterns. Acrylic tube (1.7m long, 11 mm I.D.) and the split vane type mixing vane were used, and ring-type conductance probes were used to measure the liquid film thickness in annular flow. Experimental results show that, (a) bubbly-to slug flow transition and churn-to-annular flow transition occur respectively near the mixing vane compared to the tests without mixing vane, (b) in bubbly flow region, the mixing vane breaks the bubbles into smaller ones and forwards bubbles to the center region of the tube by the centrifugal force , (c) the liquid film thickness in annular flow is decreased near the mixing vane for mass fluxes.

1. Introduction

It is generally known that spacer grids and mixing vanes in rod bundles affect the magnitude and location of the critical heat flux (CHF). The spacer grid is a device that provides uniform gaps between fuel rods and prevents the vibration of rods. Mixing vanes are attached to the spacers to increase the CHF by promoting turbulent mixing or inducing swirl flow. Many researchers have investigated the effects of those devices on the CHF as summarized by Chung [1]. Until now, most works have been concentrated on high-pressure and high-flow systems. In those systems, the mixing vanes or spacers generally increase the CHF due to several mechanisms, including: tripping the liquid film off the unheated surface, improving subchannel mixing, reducing the enthalpy imbalance, directing entrained liquid to heated wall by mixing vane (in annular flow), breakup of large bubbles or bubble crowding. Major affecting mechanisms are dependent on the subchannel geometry and flow conditions; however, fundamental understanding of the affecting mechanisms is not satisfactory. Therefore, modeling of mixing vane effects is mainly empirical based on the test data obtained from prototype test sections.

While the low-pressure and low-flow (LPLF) region is important for accident analysis, there exists only a little literature on the mixing vane or spacer effects for LPLF conditions. Becker [2] reported that the spacer grid effect on the LPLF CHF was almost negligible. Chung [1] performed an experimental study using test sections of simple geometry (an annulus and a round tube) to improve fundamental understanding of those effects at LPLF conditions. It was found that mixing vanes or spacers increased the CHF for flow rates above a threshold (~ 100 kg/m^2s). However, they did not affect or even decreased the CHF for flow rates below the threshold.

In this work, air-water tests are performed to find the mixing vane effect on the flow regime, bubble behaviors for the bubbly flow and the liquid film thickness for the annular flow using mixing vane, liquid film thickness measuring probe, and transparent acrylic tube. The effect of mixing vane is also recorded and described in various flow regimes.

2. Background

2.1 CHF experiment with a mixing vane in low pressure low flow condition

CHF experiment was performed with tube test section to investigate the effects of mixing vane [1]. The length and inner diameter of tube test section is 70 cm and 10.8 mm respectively. A 10 cm long unheated stainless steel tube is provided at the upstream to reduce the entrance effect. To get the effect of swirl rotation on the CHF, a mixing vane was used. The mixing vane was attached on a nonconductor covered wire in the tube, and the wire was fixed at both ends of the tube. At each set of test, the mass flow rate was varied from 20 to 100 kg/m^{2}sec. The inlet temperature was maintained about 37 °C and the loop pressure was about 110 kPa. The effect of the single mixing vane on the CHF was not observed when its location was relatively far from the downstream end of the test section (40cm and 15cm). For other locations (10cm, 8cm and 5cm), however, the mixing vane effect was observed. The CHF was increased by the mixing vane for mass fluxes above a certain threshold (100-150kg/m^{2}s), while it was decreased below this threshold. In higher flow region, the increase rate of CHF increased from the center position to the downstream. Here, it is worth to concentrate on the location of CHF. When the mass flux is not very low (G>50 kg/m^{2}sec) and mixing vane is located near the downstream end (5cm, 8cm), burnout occurs just below the mixing vane. Otherwise, the first CHF location is almost as same as that for the bare tube, i.e. the downstream end. For very low mass fluxes (G<50 kg/m^{2}sec) the location of CHF occurrence is observed to be random (Table 1). In the bare test section, the local CHF decreases along the axial flow direction due to the increase of fluid enthalpy and shows the minimum at the downstream end; therefore the CHF usually occurs at the downstream end. However a mixing vane increases the local CHF abruptly just downstream of its location,. The effect of the vane on the local CHF decays probably exponentially along the tube length. According to above results, the distance on which mixing vane can have an effect is about 10 to 15cm from the end of mixing vane in downstream.

2.2 The possible mechanisms of the CHF with mixing vane

In the bubbly flow regime, the bubble population density increases with the heat flux and a bubble boundary layer often forms a short distance away from the surface. The presence of rod spacing devices, which contact the rods over large sections of the rod periphery, tends to increase the turbulence near the heated surface and break up the bubble boundary layer. This could prevent dryout caused by microlayer evaporation and coalescence. The mixing vane or mixing promoter rotates the water, in other words the swirl rotation is generated. When the water in tube rotates, the centrifugal acceleration is produced and enables the liquid which has heavier density to move outside (the heated wall). Therefore, the heated wall can be easily cooled and the CHF increases. In annular flow, a very large fraction of the liquid is entrained in the core of the flow channel. Increases in CHF can be obtained by directing this entrained liquid towards the heated surface using twisted tapes or mixing vanes attached to the rod spacing devices. The effect can be stronger by the centrifugal acceleration induced by the mixing vane. If the liquid film goes through the spacer grid or mixing vane, it can be destroyed or gets thinner, and the burnout occurs in lower heat fluxes. Therefore, the increasing effect (entrained liquid) and the decreasing effect (breakup of liquid film) exist together. The possible CHF mechanisms for bubbly and annular flow are summarized in Table 2.

3. Experiments

3.1 Measurement of LFT

In annular flow regime, the mixing vane affect liquid film thickness in the manner of breaking the liquid film, directing liquid drops to the tube wall, and inducing swirl rotation. These effects are able to increase or decrease liquid film thickness. Wettability of the heated surface, which has relation with wettability in high quality region (annular region), is directly connected with CHF. Therefore, the liquid film thickness can be considered as one of the parameters to determine the CHF.

The film conductance method can be used to give a continuous record of film thickness [3]. This consists of measuring conductance between two electrodes. The major advantages of this technique are the simplicity of application and the relatively low cost of the equipment involved. Ring-type electrodes, covering the entire circumference, used in present experiments are quite convenient for measurements in pipes and columns of circular cross-section [4] and high frequency excitation signal (10 kHz) is used to minimize the effect of the capacitance.

The probe is calibrated by inserting non conducting rods, i.e. acrylic rods or glass rods, of known diameter in the center of the test section and filling the free space with water. Average film thickness around the circumference could be measured by using the pair of ring electrodes.

3.2 Experimental apparatus and ranges

The experimental loop for this experiment is a semi-closed circulation loop. The loop consists of a test section, a separator, a mixer, a centrifugal pump, water rotameters, air rotameters, valves and an air source. Lines for water supply and drain are also provided. The loop is schematically shown in Fig. 1. The working fluid is city water and air. To measure a broad range flow rate, four rotameters are used for water and air. Test section is a acrylic tube which has 170 cm length, 11 mm inner diameter(similar to inner diameter of test section used in CHF experiment) and 2 mm thickness. Tube test section is connected with a mixer and a sensor by clamps which are made with Teflon. The length of mixing vane is about 3 cm and it is made with stainless steel. The mixing vane is attached on a nonconductor covered wire in the tube, and the wire is fixed at the ends of the separator and the mixer. The position of mixing vane is changed by the movement of the wire.

Water and air flow rates to find the effect of flow regime are 0.02~20 and 52.4~1400 kg/m^{2}s, respectively. Experiments to find the effect of mixing vane on bubble behavior for bubbly flow and the liquid film thickness for annular flow are accomplished for the ranges of table 3 a) & b), respectively.

4. Results and Discussion

4.1 Flow patterns with mixing vane

In the present study, the raw signal and probability density function from the conductance probe were used for classifying the flow patterns. Flow patterns were observed for three cases, i.e. without mixing vane, with mixing vane at 10 cm and 25 cm below the probe (Fig. 1). Here, z , as shown in Fig.

l, is the distance of the mixing vane from center of the probe. The flow pattern maps based on the experimental data are shown for with and without mixing vane (Fig. 2), respectively.

According to the experimental results, at z = 10 cm, the bubbly-to-slug flow transition occur at higher liquid velocity, compared to the tests without mixing vane. This may be induced by the bubbles gathering due to the mixing vane and centrifugal force. Also the churn-to-annular flow transition occur at higher liquid velocity. This may be induced by the break of liquid slug. However, when z is 25 cm, there is no typical change compared to the experiments without the mixing vane.

4.2 Bubbly flow with mixing vane

The behavior of the bubbles for bubbly flow regime are shown in Fig. 3. The bubbles below the mixing vane are uniformly distributed in the tube, however, the bubbles are gathered on the center of the tube by swirl rotation due to the existence of the mixing vane. In addition, bubble size decreases passing through the mixing vane and this may be induced by the swirl rotation or the knife edge of the mixing vane. The diameter of bubbles passing through the mixing vane becomes smaller with increase of water flow rate. In low water flow rate, the bubble diameter is recovered to original size, i.e. the bubble size before passing through the mixing vane. However, in high water flow rate, the decreased bubble size due to the existence of mixing vane is not changed in downstream. It maybe be related to the decay of swirl rotation. Contrary to water flow rate, air flow rate has no significant effect on the bubble size in present experimental ranges.

4.3 Annular flow with mixing vane

Liquid film thickness was measured with the distance z, from -4 to 40 cm, as shown in Fig. 4. Liquid film thickness increases with the increase of the water flow rate and the decrease of the air flow rate. This trend is reasonable. Liquid film thickness sharply decreases to less than the half of original thickness, which is the thickness without the mixing vane, between z = -4 cm and z = 0 cm. The decrease of the thickness may be induced by following reasons: (a) the break of liquid film due to the detachment of mixing vane to the tube wall, (b) directing the air to tube wall due to the vane, (c) increase of liquid film velocity due to the rotation and the decrease of the cross section. However, the liquid film thickness recovers the original thickness with distance from the mixing vane for all of the experiments. This may be occurred from the decay of swirl rotation and the detachment of droplets.

5. Conclusions

In present work, air-water tests are performed to find the mixing vane effect on the flow pattern map, bubble behavior for bubbly flow and liquid film thickness for annular flow. According to the experiments, following items are obtained:

- Bubbly-to slug flow transition and churn-to-annular flow transition occur respectively near the mixing vane compared to the tests without mixing vane.
- In bubbly flow region, the mixing vane breaks the bubbles into smaller ones and forwards bubbles to the center region of the tube by the centrifugal force.
- The liquid film thickness in annular flow is decreased near the mixing vane for mass fluxes in the range of 100-1000 kg/m^{2}s.

Reference

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Table 1. The location of the first CHF occurrence in tube test section

Mixing vane location (from the end)	**Lower mass flux (G < 40 kg/m^{2}sec)**	**Higher mass flux (G : 40 - 400 kg/m^{2}sec)**
Bare	Randomly	ch.1 (the end of heater)
5cm(ch.1 - ch.2)	Randomly	ch.2, 3 (just below the mixing vane)
8cm(ch.2 - ch.3)	Randomly	Usually ch.3, a few times ch.1 and ch.3 simultaneously
10cm(ch.2 - ch.3)	Randomly	Usually ch.1, 2
15cm(ch.4 - ch.5)	Randomly	ch.1 (same as bare)
40cm(ch.6 - ch.7)	Randomly	ch.1 (same as bare)

Table 2. The effects of the mixing vane on the CHF

Region	**Effects**	**CHF**
General	Enthalpy mixing increases	increase
Low quality (Subcooled, Bubbly)	Breakup of bubble crowding	increase
	Centrifugal acceleration	increase
High quality (Annular, Churn)	Increase of liquid deposition by directing the entrainments to the wall	increase
	Breakup of liquid film	decrease

Table 3. Test matrix for the experiments

Q_g =	0.0611	0.122	0.163
Q_f= 524			
1048			
1397			

a) bubbly flow (kg/m^{2}s)

Q_g =	20.4	30.6
Q_f= 105		
350		
993		

b) annular flow (kg/m^{2}s)

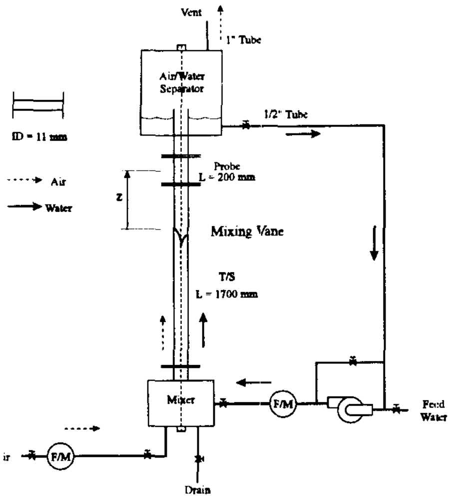
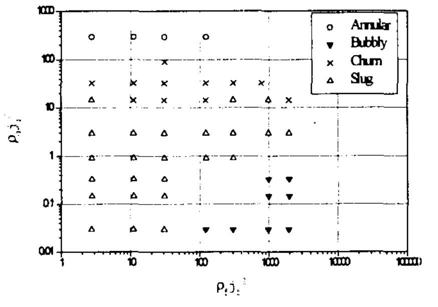
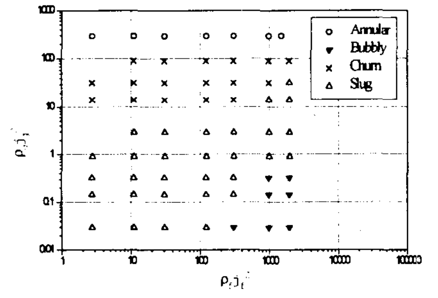


Fig. 1 Schematic diagram of experimental loop

Fig. 3 Bubbly flow with mixing vane



(a) without mixing vane



(b) with mixing vane (z = 10 cm)

Fig. 2 Flow pattern map

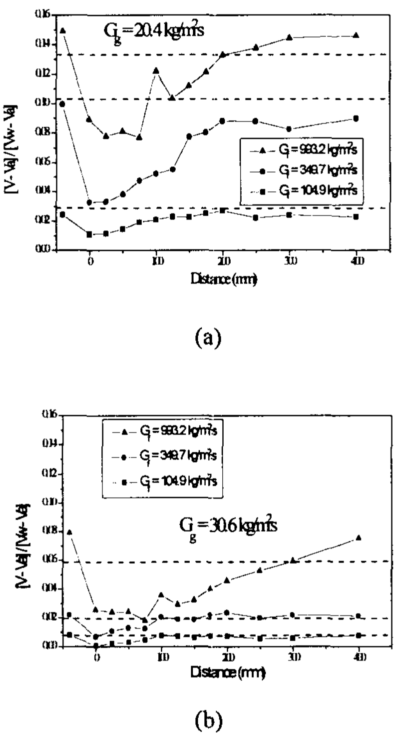


Fig. 4 Liquid film thickness