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Nondestructive Inspection for Boiling Flow in Plate Heat Exchanger by Neutron Radiography

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Abstract
Boiling two-phase flows in a single-channel commercial brazing plate heat exchanger were visualized by thermal neutron radiography method, and the effect of flow direction, such as vertically upward or downward, on liquid distribution in the channel and boiling heat transfer performance was considered. The experiments had been carried out using thermal neutron radiography facility of JRR-3 of JAEA in Japan. The relationship between heat transfer coefficients and flow behaviors for three kinds of inlet condition, such as subcooled liquid, saturated liquid, and wet vapor, was investigated. Though vertically upward flow is generally selected for boiling flow to remove vapor bubble from heating surface by buoyancy force, it was shown from the result that downward boiling flow produced higher heat transfer performance than upward flow. Especially, the tendency was remarkable at low quality condition. From the visualization results, it could be clearly observed that there was a large difference between upward and downward in flow pattern around the inlet. As the results, it was shown that the lowering of heat transfer performance was caused by the difference of flow pattern.

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1. Introduction

Recently, more compact and higher performance heat exchanger is required for efficient utilization of heat energy, energy saving, and compactness of equipments. In order to satisfy these requirements, it is necessary to increase heat transfer area per unit volume and to improve heat transfer coefficient. For such needs, plate heat exchanger (PHE) has become of interest. A plate heat exchanger is made by brazing 20-280 sheets of wavy thin stainless steel sheets. Each fluid flows between the sheets alternately, that is, a plate exchanger has many parallel channels. The each channel has netlike conduits formed by wave configuration of sheets. The configuration leads to larger heat transfer area and higher heat transfer coefficient, but also induces larger pressure loss. Although plate heat exchanger is used primarily for liquid-to-liquid heat transfer, its performance is expected to be also good in evaporation and condensation applications. Therefore, it has been introduced to the refrigerating cycles as evaporators or condensers. In the application for gas-liquid two-phase mixture the dynamic flow behaviors may strongly affect the heat transfer performance. Unfortunately, conventional studies were mainly focused on the single-phase heat transfer [1]. Though there are some papers on two-phase flow characteristics in a plate heat exchanger discussed with flow pattern [2,3], those are usually for treated adiabatic flow of air and water mixture. There is no paper on flow pattern of boiling flow.

This study deals with the relationship between boiling heat transfer performance and flow pattern for a single channel plate heat exchanger. Especially the effect of flow direction, such as vertically upward and downward, on the flow and heat transfer characteristics. Flows were visualized by neutron radiography.

2. Experimental setup and tested PHE

A schematic diagram of experimental setup is shown in Fig.1. Hydro-chloro-fluolo- carbon HCFC-142b (CH_3CFCl_2) was used as working fluid. Fluolo-carbon FC-3283 without hydrogen was selected as heating medium because of its low neutron attenuation. The working fluid in a tank *1* was fed by a gear pump *3* to the test section through a liquid flow meter after setting an inlet condition by a subcool control heater *4* and quality control heater *5*. The test section 6 was vertically placed in an irradiation room of real-time neutron radiography facility in JRR-3 of Japan Atomic Energy Agency. Flow direction was controlled by four-way ball valve *8*. On the other hand, the heating medium was supplied to the PHE from a constant temperature bath in the opposite direction to working fluid flow. The PHE has three channels by 4 thin SUS wavy sheets. The working fluid in the center channel was heated by the heating medium in the both sides channel. Neutron beam was irradiated vertically to plates, and boiling behavior was visualized.

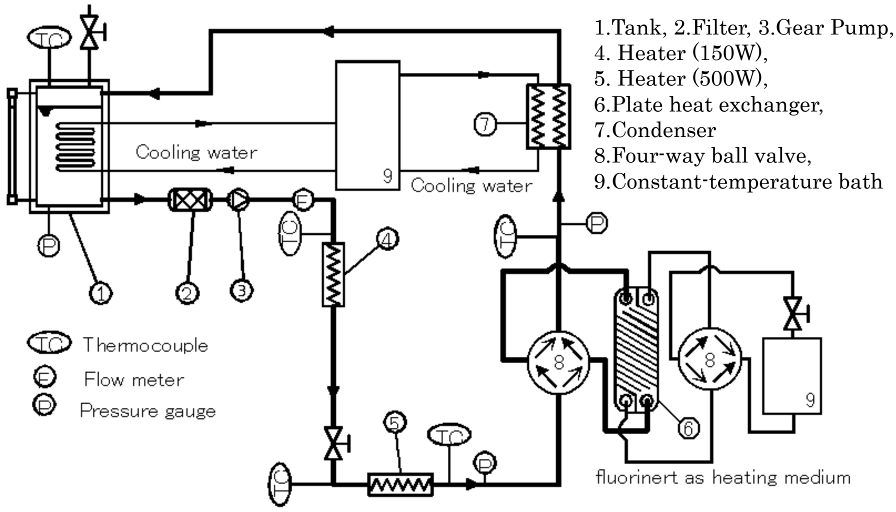

Fig.1 Schematic diagram of experimental setup.

The detail of plate configuration is shown in Fig.2. The plate is the same as commercial product by Hisaka works ltd. Japan. Plates of thickness 0.5mm were formed with press, and the surface of plate was ribbed type. The rib patterns on adjacent plates are leftside-right. These ribs form netlike conduits. The heat transfer area of a plate is 0.0123 m^2, and the volume of single channel is 0.02 L. The average hydraulic diameter of the single net-like channel is calculated to 3.36 mm. The port of working fluid is indicated by x and y in Fig.2

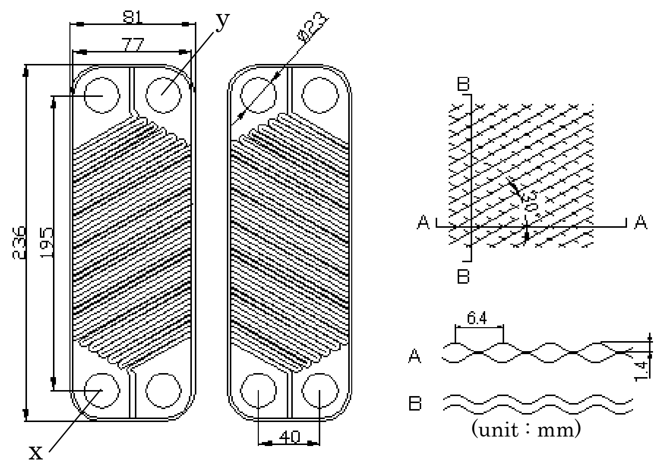

Fig.2 Plate configuration.

Original radiographs of the test section with liquid single phase flow and without working fluid are shown in Fig.3 (a), (i) and (ii), respectively. From these two images, only liquid can be visualized by comparison operator of brightness. Processed image is shown in Fig.(b). Brightness becomes lower with thicker liquid thickness. Since the image (i) is for liquid single-phase flow, the black net shows the channel of working fluid.

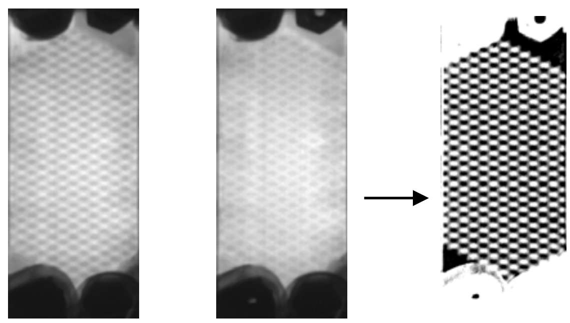
(i) Liquid single-phase. (ii) Without liquid. (a) Original image. (b) Processed image for liquid visualization.

Fig.3 Image processing to visualize liquid behavior.

The system pressure was at atmospheric pressure. As experimental conditions, the mass flow rate of working fluid G_f was varied in the range of 0.0052 to 0.026 kg/s, for the inlet subcooling condition with the subcooling degree ΔT_{subin} of 10 K, inlet saturated liquid condition, and inlet two-phase mixture condition with the quality of 0.01.

3. Experimental results and discussion

3.1 Heat transfer performance of the PHE

Experimental results of heat transfer rate and overall heat transfer coefficient are plotted in Fig.4 and 5 against mass flow rate G_f, respectively. The results for upward flows are plotted by open symbols and those for downward flows are plotted by closed symbols. It can be seen from Fig.4 that heat transfer rate decreased with increasing mass flow rate of working fluid, and was higher for inlet subcooling condition than inlet wet vapor condition. These reasons might be on temperature difference between working fluid and heating medium. The effect of flow direction cannot be clearly observed in heat transfer coefficient. To evaluate heat transfer performance, overall heat transfer coefficient was calculated by using logarithmic mean temperature difference calculated from terminal temperatures of both fluids. Since for inlet subcooling condition temperature gradient should change at incipient boiling point, logarithmic mean temperature difference was compensated according to flow condition, subcooling or saturating condition. The detail of calculation methods had been reported by L. Jiang, et al. [4]. Calculated results of overall heat transfer coefficient are plotted in Fig.5 with the same symbols with those in Fig.4. It can been seen that the downward flow produced higher heat transfer performance than the upward flow. Since the effect of the flow direction should be little in single-phase flow region, heat transfer coefficients in two-phase flow were affecting by the flow direction.

Generally designers of heat exchanger think for boiling flow that heat transfer performance of downward flow in a tube might be lower than upward flow, because buoyancy operates in the opposite direction to main flow and slip velocity between liquid and vapor becomes lower. However, downward flow produced higher heat transfer performance in the plate heat exchanger. Since the difference was caused by flow pattern difference between upward and downward flow, flow pattern of two-phase flow in plate heat exchanger should be visualized and understood.

3.2 Flow visualization by neutron radiography

Visualized images of liquid behavior are shown in Figs.6. Figs.(i) are boiling behavior for inlet subcooling condition, and Figs. (ii) are those for inlet wet vapor condition for upward flows in Figs.(a) and downward flows in Figs.(b),

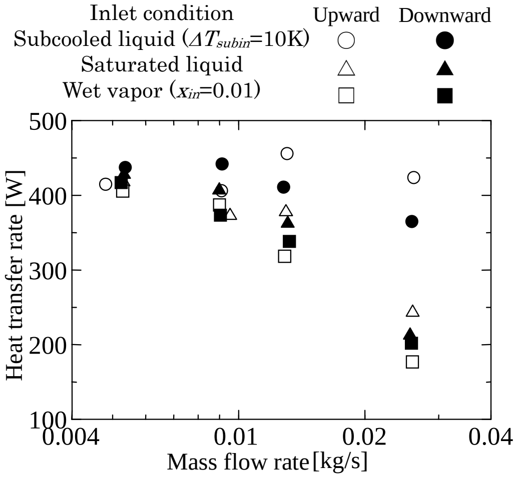

Fig. 4. Heat transfer rate.

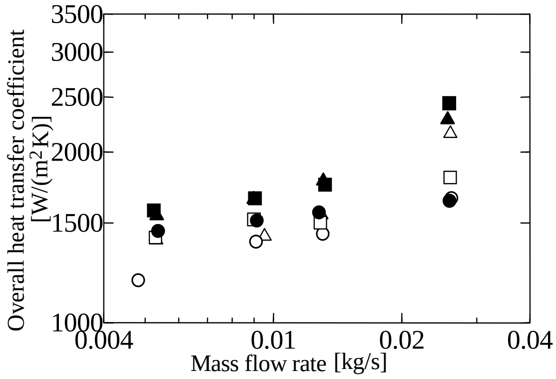

Fig. 5. Overall heat transfer coefficient.

respectively. Three continuous frames with the interval of 2/30 seconds are shown for each figure. Darker part shows thicker liquid thickness. The detail of image processing method is reported by H. Asano, et al.[5].

For inlet subcooling condition, the area where boiling occurred can be clearly observed. Single-phase flow area was larger at the center of channel for each direction. The reason might be on liquid flow rate distribution, that is, liquid flow rate around the center might be higher. Boiling two-phase flow area for downward flow was larger than that for upward flow. In this case, there is little difference in overall heat transfer ere coefficient.

For upward flow with inlet wet vapor condition, vapor flowed into the test section, intermittently. Liquid stagnation was observed at the both side around the inlet. Heat transfer might be lower in the area with liquid stagnation. On the other hand, for downward flow with inlet wet vapor condition, though vapor flowed into the test section intermittently, liquid stagnation was not observed. The difference in flow pattern leaded to difference in heat transfer coefficient.

Time-average two-dimensional void fraction had been successfully obtained from still images by high spatial resolution cooled CCD camera. Still image has 100 μm/pixel of spatial resolution and 16 bit of intensity level. The detail of the method for quantitative measurement was reported by H. Asano [5]. Cross-sectional average void fraction was calculated, and the results are plotted in Fig.6 against the distance from the inlet. Cross-sectional average void fraction is important to estimate gas and liquid mean velocity. Periodical fluctuation was observed in both void fraction distribution. The fluctuation might be caused by the channel configuration. Void fraction was low due to liquid stagnation at the node of netlike channel. Void fraction for downward flow around the inlet was higher than that for upward flow due to the liquid stagnation in the upward boiling flow. The void fraction was influenced by the flow behavior around the inlet, and void fraction for downward flow was higher in the almost entire range. However, since the difference was a little around the outlet, it can be said that the effect of flow direction on void fraction in developed area was a little.

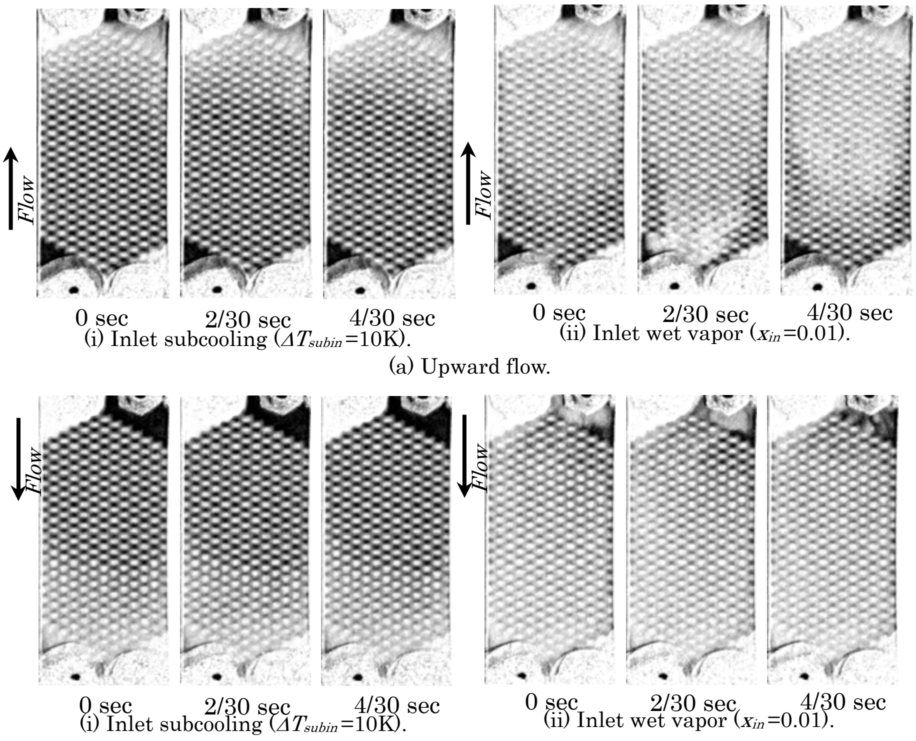

Fig.6 Liquid flow behaviors in boiling two-phase flow.
Effect of inlet condition and flow direction (Mass flow rate : 0.026 kg/s)

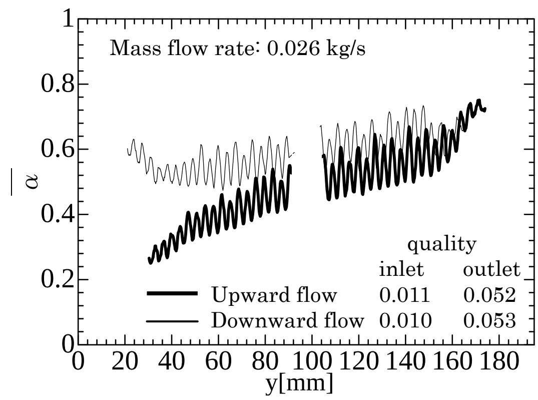

Fig.7 Flow direction distribution of cross-sectional average void fraction.

4. Conclusions

Boiling flows in a single-channel commercial brazing plate heat exchanger were visualized and void fractions were measured by thermal neutron radiography. Effect of flow direction on heat transfer performance was investigated. It was shown from the results, heat transfer of downward flow was higher that of upward flow because liquid stagnant area was larger for upward flow.

Acknowledgment

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