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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. The results show that the lowering of heat transfer performance was caused by the difference of flow pattern.

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], 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 both the sides channel. Neutron

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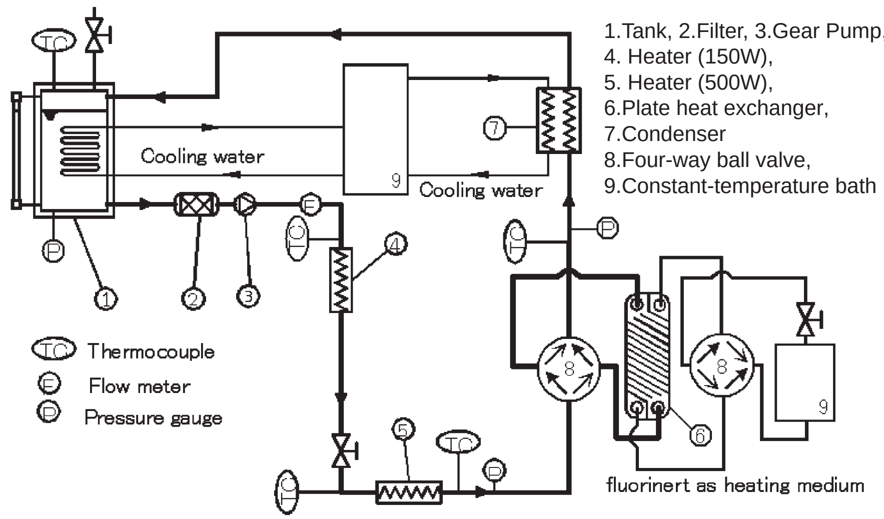

Fig. 1. Schematic diagram of experimental setup.

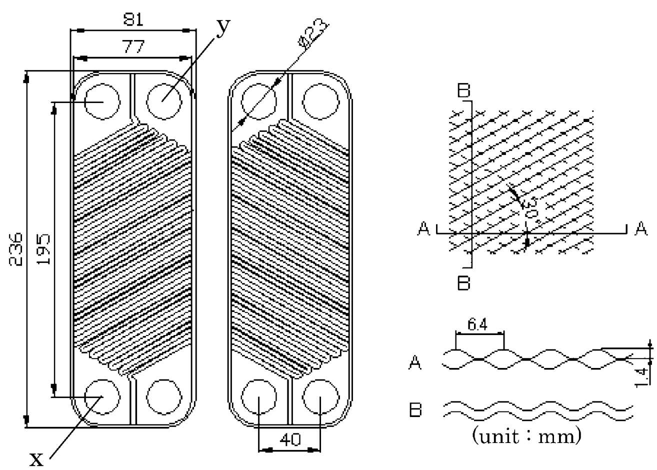

Fig. 2. Plate configuration.

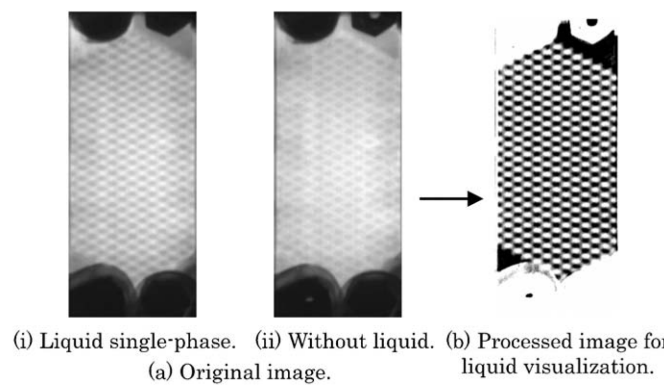

Fig. 3. Image processing to visualize liquid behavior.

beam was irradiated vertically to plates, and boiling behavior was visualized.

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 0.5 mm were formed with the press, and the surface of plate was the 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 a 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

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 a comparison operator of brightness. Processed image is shown in Fig. 3(b). Brightness becomes lower with thicker liquid thickness. Since image (i) is for liquid single-phase flow, the black net shows the channel of working fluid.

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 0.0052–0.026 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 Figs. 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 Jiang et al. [3]. Calculated results of overall heat transfer coefficient are plotted in Fig. 5 with the same symbols with those in Fig. 4. It can be 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