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Flow behavior of rapid thermal oscillation inside an asymmetric micro pulsating heat exchanger

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ABSTRACT

This study has investigated the rapid thermal oscillatory flow in an asymmetric micro pulsating heat exchanger (MPHE). In the design and fabrication of the MPHE, a transparent acrylic plate was attached to the stainless steel plate on which 14 parallel rectangular channels were formed. As working fluids, FC-72 and ethanol were tested. The fluid inside the micro channel moves rapidly with pulsating motions by swelling and shrinking of liquid slug/gas plug at evaporation and condensation sections. By measuring the temperature variations from start-up to steady state operation, the effective thermal conductivities were evaluated. Since the filling ratio of working fluid plays an important role in heat exchanger efficiency, the optimum filling ratio was found for each working fluid. From the flow visualization inside the MPHE filled with FC-72, two different flow modes – oscillatory eruption mode and circulation mode – occurs according to the filling ratio. The circulating motion which occurs at the optimum filling ratio, helps the heat transfer into the cooling water more active than the oscillatory eruption mode.

1. Introduction

Electronic devices become smaller and more integrated due to the enhanced fabrication technology. However, how to remove the heat generated from small electronic devices is a recent issue in order to prevent the breakdown of the devices [1]. There are many kinds of heat exchanger system but more compact and more efficient system is required to cool such a small electronic devices [2]. Heat pipe is a well-known device for the heat transfer system of small size and high temperature. Heat pipes have been classified into two different types, one is a thermosyphon type using the gravity force and the other is a wick type using capillary force. However, theses heat pipes have a problem of blockage caused by gas-plug and liquid-slug inside a tube when the diameter of the heat pipe gets smaller [3].

There have been many studies on the new types of heat exchanger to overcome the failure of operation in traditional heat pipes. A pulsating heat pipe (PHP) which Akachi [4] first introduced in his patent, might be an alternative. The PHP utilizes the operating force by thermal swelling and shrinking of plug and slug flows inside a small channel. This swelling and shrinking flows are repeated several times per second, which leads to a pulsating phenomenon in a multi-channel system. Xu and Zhang [5] found a temperature overshoot during the start-up period of PHP and estimated the characteristic frequency in steady thermal oscillation. The flow patterns such as oscillation and circulation were measured by Khandekar and Groll [6], who mentioned that although their PHP had only one loop, a circulating motion was occurred with the increase of heat input power. Qu et al. [7] reported that the flow pattern inside a PHP varied from thermosyphon-type flow to oscillating and circulating flows with the increase of heat input power.

In an effort to reduce the size, Nadgauda [8] in his thesis, introduced a fabrication method of micro heat exchanger using MEMS techniques. Lim et al. [9] fabricated a copper plate heat exchanger with microgrooves of 0.15 mm by a femtosecond laser technique. Youn and Kim [10] fabricated successfully a silicon-based micro pulsating heat spreader (MPHS), where the hydraulic diameter of the micro channels was 0.57 mm. Palkar [11], in his thesis, fabricated a subminiature micro heat exchanger with the full size of $9.5 \times 4.3\ mm^2$. In order to increase efficiency, Chien et al. [12] proposed a new shape of MPHP which was made up of asymmetrical micro channels, based on the concept that the variation of the channel diameter results in different frictional force in multi-channel system so that working fluid moves in one direction. Thompson et al. [13] designed a plate heat pipe with staggered micro channels to introduce three-dimensional thermal flows.

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Other researchers [14,15] contributed to the numerical simulations of fluid momentum and meniscus movement inside the PHP during oscillation period. However, the variation of temperature on the condenser section and heat transport process by the circulating motion has not been clearly understood yet.

The present study focuses on the operational modes of thermal flows in a micro pulsating heat exchanger (MPHE) in order to investigate how the liquid slug and gas plug at evaporation and condensation sections affect the heat transport process. A MPHE with asymmetric micro channels is fabricated transparently to visualize the thermal flows inside the micro channels. FC-72 and ethanol are used as working fluids. The effective thermal conductivities of the working fluids are measured and the optimum filling ratios are compared according to the two working fluids. From the simultaneous measurement of pressure, temperature and the visualization images of the MPHE under vertical operation, the flow modes according to the filling ratio are classified and their thermal effects on heat transfer are discussed.

2. Experiments

Fig. 1 shows a MPHE specimen tested in this study in order to visualize the micro flows. The MPHE specimen was made by a micromachining technique. The micro channels with a thickness of 1.0 mm were made from stainless steel. An acrylic plate was attached onto the stainless steel channels using a chemical bonding process. Thus, the MPHE specimen is transparent on front side and the whole size is 44 × 22.5 mm^2. The widths of 14 parallel rectangular channels are 0.5 mm and 1.0 mm alternately. The height of channel is 0.5 mm. Fig. 2 shows the image of the assembled MPHE specimen for experiments. The teflon was used as a housing material, which insulates the bottom of the specimen. The lengths of evaporator and condenser sections are 15 mm and the length of adiabatic section is 14 mm.

Fig. 3 shows the schematic of the experimental setup. A vacuum pump removes the non-condensable gases in the working fluid, which prevents the drastic decrease of performance. The MPHE was charged with two kinds of working fluids (FC-72 and ethanol at Table 1) by tightly controlling the amount of fluids using a syringe pump. The filling ratio, φ is defined as the ratio of the amount of working fluid to the total volume of channels which is calculated by multiplying the cross section area of channel by the total length of fluid columns based on the visualization image. Onto the bottom of evaporator, a flat heater was attached which was connected to an AC power supply. The input voltage to the flat heater was measured by a digital multi-meter. The bottom of condenser was cooled by cooling water, which was circulated from a constant-temperature bath. The inlet and outlet temperatures of the cooling water passing through the cooling jacket were measured by two K-type thermocouples to evaluate the heat transfer rate in the condenser section. In addition, other thermocouples were attached onto the bottom of the stainless steel plate to measure wall temperatures of the evaporator and condenser. To measure the variation of pressure in the MPHE, a pressure sensor was inserted into a fluid injection port. The temperature and pressure signals were collected by a data acquisition system. The motion of flow meniscus is observed using a high-speed CCD camera (SVSI).

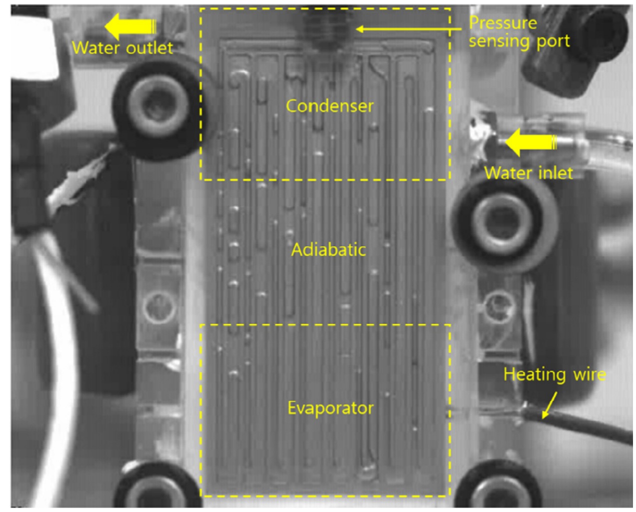

Fig. 2. Image of the assembled MPHE specimen.

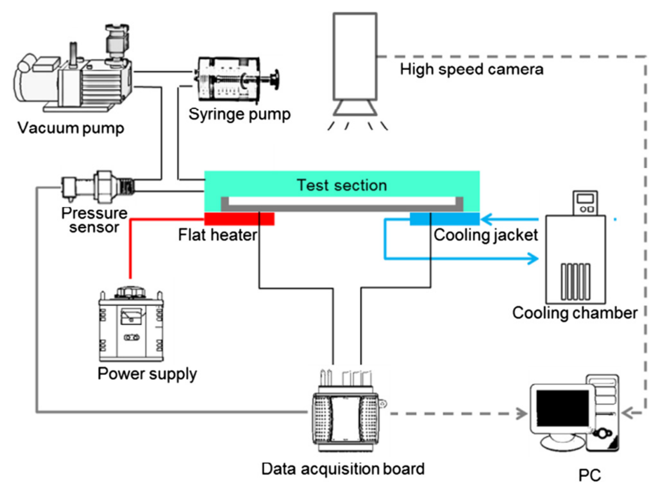

Fig. 3. Schematic of the experimental setup.

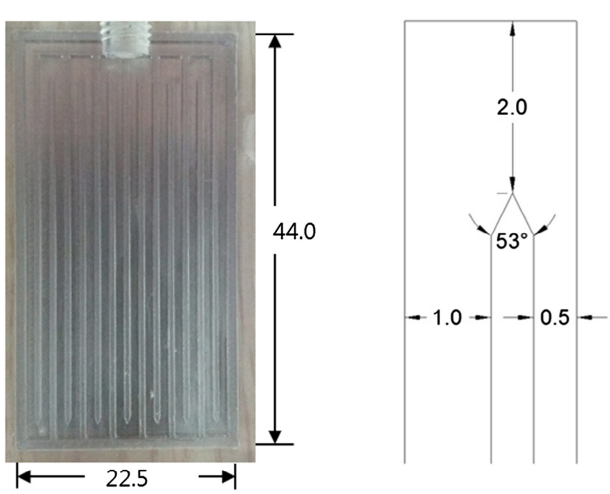

Fig. 1. An asymmetric MPHE specimen to visualize the micro flow.

3. Results and discussion

3.1. Start-up behavior

In order to prevent thermal damage of micro electric devices, the start-up temperature and time are crucial parameter for thermal responsivity of MPHE. Figs. 4 and 5 show the variations of wall temperature with time for the MPHE charged with FC-72 and ethanol, respectively, after the heating power input is imposed. The temperature of evaporator ($T_{evap.}$) and condenser ($T_{cond.}$) varies