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Experimental investigation of heat transport with oscillating liquid column in pulsating heat pipe using forced oscillation system

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ABSTRACT

To clarify the detailed heat-transport mechanism of a pulsating heat pipe, an experimental study was conducted using a forced oscillation system. A liquid column was oscillated in a channel for a single-component (liquid ethanol and vapor ethanol) system and a two-component (liquid ethanol and air) system. In the single-component system, the sensible heat transport due to the oscillating flow and the latent heat transport due to the phase change occurred simultaneously because the gas phase consisted of only working-fluid vapor. In the two-component system, only sensible heat transport occurred, because the gas phase consisted of air at the atmospheric pressure. The effective thermal conductivity of the latent heat transport was determined according to the difference in effective thermal conductivity between the single-component system and the two-component system. The effective thermal conductivity of the sensible heat transport increased monotonically as the oscillation center moved to the heating section under the same amplitude and frequency. On the other hand, the effective thermal conductivity of the latent heat transport increased as the oscillation center moved to the cooling section under the same amplitude and frequency until the tip of the oscillating liquid column reached the heating section. The vapor-mass fluctuation was estimated according to the measurement of the vapor-pressure fluctuation in the single-component system. The results show that the liquid film formed by the oscillating liquid column played an important role in the mechanism of the latent heat transport. They also show that the direct-contact condensation from the working-fluid vapor to the tip of the liquid column occurred when the liquid column moved from the cooling section to the heating section.

1. Introduction

Small and highly efficient heat-transport devices are needed to cool semiconductor chips with the increase in the power dissipation. Heat pipes are among these heat-transport devices. Among the various types of heat pipes, wick heat pipes and thermosyphons are typically used [1]. These heat pipes use the latent heat of the evaporation and condensation of the working fluid for heat transport. Pulsating heat pipes (PHPs), which were originally proposed by Akachi et al. [2], have a different heat-transport mechanism from conventional heat pipes such as wick heat pipes and thermosyphons and have attracted considerable attention as a new type of high-performance and simple-structure heat-transport device [3]. A PHP consists of a single meandering capillary tube between a heating section and cooling section, as shown in Fig. 1(a). The tube is evacuated and partially filled with working fluid. Several liquid columns are formed by surface tension. The pressure difference between the heating section and cooling section causes the oscillation of the liquid columns.

PHPs have been widely investigated, ranging from fundamental studies for understanding the operating mechanism to applied studies for improving the heat-transport performance. Because this paper focuses on the heat-transport mechanism, the fundamental studies are surveyed as follows. To observe the behavior of the working fluid in the tube, numerous experimental studies using transparent glass tubes have been conducted. In a visualization experiment using a glass tube, Hosoda et al. [4] and Nishio et al. [5] observed the vapor-liquid two-phase flow in the tube using a high-speed video camera. They observed simple periodic flow patterns at a high filling ratio of the working fluid and estimated the latent heat-transport rate with the phase change of the working fluid according to the fluctuation of the length of the vapor plug. Shafii et al. [6] proposed a simple mathematical model for the flow of liquid slugs and vapor plugs in PHPs. They assumed that the evaporation and condensation heat-transfer coefficients were

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Nomenclature

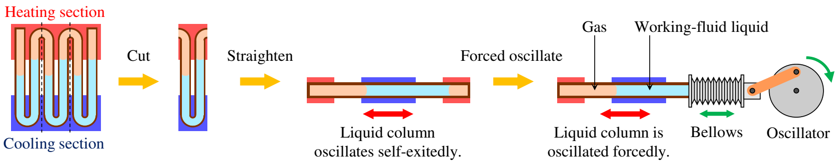
A	cross section (m^2)
f	oscillation frequency (Hz)
k	thermal conductivity (W/m·K)
m	mass (kg)
Q	heat-transport rate (W)
R	gas constant (J/kg·K)
S	oscillation amplitude (m)
T	temperature (°C)
t	time (s)
V	volume (m^3)
x	position (m)

Greek

γ	specific-heat ratio (–)
Θ	dimensionless wall temperature (–)

Subscript

ad	adiabatic change
av	average
c	center
cond	heat conduction
E	electrical input power of heater
eff	effective
sat	saturated
t	tip of liquid column
w	channel wall



(a) Usual PHP. (b) One-turn PHP. (c) Straightened one-turn PHP. (d) Half-turn PHP with forced oscillation.

Fig. 1. Schematic of the experimental method used in the present study.

constant. Zhang et al. [7] improved the model proposed by Shafii et al. [6]. The improved model includes an analysis of thin-film evaporation and condensation. Shafii et al. [6] and Zhang et al. [7] reported that the heat transfer in PHPs is mainly due to sensible heat transport. Dobson [8,9] studied the mechanism of a PHP with open ends using a simple model that considers the effect of the liquid film. In this model, the thickness of the liquid film and the heat-transfer coefficient of the phase change are regarded as constants. Das et al. [10] presented experimental data for a simple PHP comprising a capillary tube connected to a reservoir and proposed a film evaporation-condensation model to account for the two-phase equilibrium at the vapor-liquid interface. They compared experimental results with numerical results based on the film evaporation-condensation model. In addition, Nikolayev [11] applied the film evaporation-condensation model to simulate a multi-turn PHP. Rao et al. [12,13] reported data obtained with the improved experimental setup that was originally proposed by Das et al. The tube was fully transparent to observe the motion of the entire liquid film. This enabled an understanding of the complex liquid-film evaporation and condensation. Kato et al. [14] experimentally investigated heat transport in a PHP of a single straight tube with a liquid reservoir at the cooling section. They characterized the heat-transport mechanism by three factors: (a) the latent heat transport caused by the condensation on the liquid film, (b) the heat diffusion induced by the oscillating liquid column, and (c) the liquid exchange between the heat-transport tube and the liquid reservoir. In addition, Nagasaki et al. [15] reported the relationship between the vapor-pressure fluctuations and liquid-column oscillation in the case of a straight-channel PHP with the cooling section at the center of the channel and the heating sections at the both ends of the channel. This is the simplest single-turn PHP, as shown in Fig. 1(c).

As mentioned in the previous paragraph, although several studies have been conducted with both experimental and numerical approaches, the operating mechanism and heat-transport mechanism of PHPs have not been sufficiently clarified [16]. This is because PHPs have complex thermal hydraulic phenomena despite their simple structure. Zhang et al. [17] mentioned the relative magnitude of the sensible heat transport and latent heat transport as one of the unresolved issues affecting the performance of PHPs. Here, the sensible heat transport is based on convective heat transfer between the wall and the working fluid; that is, the oscillating working fluid receives heat from the channel wall in the heating section and releases heat to the channel wall in the cooling section. The latent heat transport is based on the phase change of the working fluid, such as evaporation mainly in the heating section and condensation mainly in the cooling section. Understanding the roles of the sensible heat and the latent heat helps to clarify the details of the heat-transport mechanism, select the optimum working fluid, and obtain guidelines for the improvement of the heat-transport performance. However, only a few studies have reported the contribution of the sensible heat and latent heat in the heat transport of PHPs. It was reported that the sensible heat transport is the majority of the overall heat transport in PHPs by an experimental study [5] and numerical studies [6,7]. This means that the contribution of the latent heat to the heat transport of PHPs is small and that the role of the evaporation and the condensation of the working fluid is mainly to oscillate the liquid slugs. On the other hand, it was mentioned that the contribution of the latent heat to the overall heat transport depends on the flow patterns [18]. It was suggested that the latent heat transport plays a significant role under an annular flow. This suggests the possibility that the long liquid film between the heating section and the cooling section observed in later studies [10,12–14] plays a significant role in the latent heat transport. As previously mentioned, the contribution of the sensible heat transport and latent heat transport in PHPs has not yet been clearly clarified. Therefore, further experimental studies are needed in order to clarify the roles of the sensible heat and latent heat in the heat transport of PHPs under various conditions.

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