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Experimental investigation of the thermal characteristics of single-turn pulsating heat pipes with an extra branch

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ABSTRACT

In addition to some approaches such as changing the working fluid or number of turns in a pulsating heat pipe (PHP), geometrical changes are also appealing for enhancing the thermal performance of this type of heat pipes. The main idea of this investigation is to increase heat transfer rate by increasing flow circulation of working fluid. By placing an additional branch in the evaporator section, a secondary bubble pump was created which improved the circulation of fluid inside PHP. In order to investigate the impact of this additional branch, two similar one-turn copper heat pipes were fabricated. One of them was the conventional PHP and the other had an additional branch and is named additional branch PHP (AB-PHP). Thermal performances of these two types of heat pipes were investigated at different filling ratios (40, 50, 60, and 70%), inclination angles (0, 30, 60, and 90°), and heat inputs (from 5 to 150 Watts). Results showed that the thermal performance of the AB-PHP is considerably (up to 51%) better than the conventional PHP in the vertical orientation using filling ratios of 40% and 70%. Furthermore, comparing the performance of these two systems at the optimum filling ratio (60%) and different inclination angles indicated the better performance of AB-PHP in non-vertical positions including horizontal position. To better understand the effect of the additional branch in the AB-PHP, a Pyrex heat pipe similar to the copper type was fabricated and the flow circulation was visually analyzed.

1. Introduction

Heat pipes are used in various applications due to their very high thermal conductance and reliability. The idea of using these devices was first proposed by Gaugler in 1942. However, the remarkable benefits of the heat pipe became known after its invention by Grover [1]. Since that time, several investigations have taken place in laboratorial and industrial studies. Indeed, many different ideas have been presented for the better performance of heat pipes.

From 1990, that the pulsating heat pipe (PHP) was invented by Akachi [2], several investigations were conducted on this novel heat transfer device due to its simple structure and absence of capillary wicks. Pulsating heat pipes have been recently used in electronic applications by embedding these devices with microelectronic chips and racks due to their high thermal conductivity, high efficiency, and suitable working temperature for electronic devices [3–5]. These types of heat pipes are available in two forms: looped and un-looped. The looped version is more popular because of its ability to produce circulation of the working fluid [6]. Due to its structural simplicity, its operating mechanism is simple as well. Working fluid evaporates and increases the vapor pressure when the evaporator is heated. This results in the growth of bubbles in the evaporator. Enlarged bubbles push the liquid towards the condenser. Unlike the evaporator, the condenser cools down the working fluid resulting in a reduction of vapor pressure and shrinkage of vapor bubbles. The growth and shrinkage of bubbles result in an oscillating motion in pulsating heat pipes. The heat transfer from the evaporator to the condenser is of sensible form within liquid slugs and of latent form in vapor bubbles [1]. However, Shafii et al. [7] showed that the majority of heat transfer in the looped and un-looped PHPs is of the sensible form.

In order to have vapor plugs and liquid slugs and to make sure that the capillary forces (surface tensions) are larger than gravitational forces, the magnitude of Bond number introduced in Eq. (1) should not be more than 2 [8].

$$Bo = \frac{D_i}{\sqrt{\frac{\sigma}{g}/(\rho_l - \rho_g)}} \tag{1}$$

This constraint ensures that the vapor bubbles remain confined within the capillary tubes. In this condition, discrete bubbles and liquid slugs will be sustained in a tube [8].

Numerous factors, including inner and outer conditions, can affect

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the heat pipe operation. During the experiments, factors such as filling ratio, tilt angle, initial pressure in the heat pipe, amount of body force (gravitational acceleration), amount of heat input, etc. can affect the results. Khandekar et al. [9] examined the effect of filling ratio on the operational characteristics of PHPs by using various working fluids in their experiments. They found that better thermal performance and self-sustained thermally driven pulsating action only occurs in the filling ratio range of 25–65% which depends on the type of working fluid. Mameli et al. [10] experimentally investigated the combined effect of inclination angle and filling ratio at different heat input levels on operation stability and thermal performance of a multi-turn PHP filled with FC-72. Their results showed that their PHP is too sensitive to gravity and its operation is unstable at high heat input levels. They found that unlike the vertical position, their PHP does not undergo any performance drop with respect to the heat input in the horizontal position. Gu et al. [11] investigated the effect of gravity on heat transfer characteristics by testing a flat plate PHP under a variety of gravity levels (1–2.5 g and 0.02 g) which was developed by means of parabolic flights. They concluded that both the orientation of the PHP and locations of the heated and cooled sections can affect heat transfer performance under normal and hypergravity conditions. In one of their experiments, in which the heating was applied at the top and the gravity was altered by different maneuvering during the flight phases, their PHP showed better heat transfer performance under reduced gravity. This result shows that, unlike the normal and hypergravity conditions, the performance of a PHP under reduced gravity is almost independent of heater location.

The working fluid has a great impact on the performance of the PHPs. Mohammadi et al. [12] fabricated a four-turn PHP and charged it with water and Ferrofluid with two different concentrations to investigate the effect of the working fluid, filling ratio, orientation, heat input, and magnetic field on the thermal performance of PHP. Their results showed that using Ferrofluid instead of distilled water results in the reduction of thermal resistance in all orientations due to the improvement of thermal conductivity, heat transfer area, and evaporator active nucleation sites.

Geometrical parameters are the essential factors that should be considered during designing pulsating heat pipes. Previously, investigators have claimed that the increase of contact area between the liquid and inner surface of the evaporator results in better thermal performance [13]. Additionally, their results indicated that fluid circulation can enhance the thermal performance, stability, and predictability of the PHPs [13–17]. Hence, the main purpose of altering the conventional geometric design of PHPs is to induce fluid circulation.

For a two-phase flow within a vertical tube, a correlation has been proposed for calculating the heat transfer coefficient [18]. Ebrahimi et al. showed that the magnitude of the proposed two-phase heat transfer coefficient is proportional to the flow velocity [17]. When a circulatory flow is formed and maintained within the PHP, the hot fluid flows continuously from the evaporator towards the condenser and the heat transfer is high due to the high-temperature difference between the hot fluid and the cold wall of the condenser. On the other hand, when an oscillatory flow is formed, the hot two-phase flow from evaporator stops before it reaches the condenser and the flow direction changes. Therefore, a continuous change in direction of fluid flow reduces the average velocity of the fluid from the evaporator to the condenser and reduces the amount of heat transfer.

Using check valves is one of the simplest solutions for enhancing flow circulation within PHPs. Accordingly, Bhuwakietkumjohn and Rittidech [19] used two check valves in their ten-turn PHP that utilized ethanol and silver Nano-ethanol mixture as working fluids to induce an uni-directional flow. They reported that the flow pattern changed from slug-plug and annular to a dispersed bubble flow in the case of using check valves. Since the use of check valve makes the PHP structure more complicated, some researchers tried other alternatives to induce fluid circulation in PHPs. Thompson et al. [14] integrated Tesla-type check valves (without any moving parts) into a multi-turn flat-plate PHP and found that circulation in the desired direction was improved and that this improvement increased with heat input. By using Tesla-valves, the thermal resistance of their PHP was reduced from 15% to 25% depending on heat input value. A similar investigation was performed by de Vries et al. [13] on a one-turn flat-plate PHP with 2 T-valves. They reached an optimized form of the Tesla-valve with the aid of single-phase flow simulations for a variety of valves. Using the optimized valve, they found a 25% difference in velocity for different flow directions in the Tesla-valve channels. Ebrahimi et al. [17] developed oblique interconnecting channels in both the evaporator and condenser sections to increase flow resistance in one direction. Their results indicated that the performance of the PHP improved noticeably by interconnecting channels in a wide range of heat inputs and filling ratios. Using PHPs with multiple pipe diameters is another approach proposed by other investigators in order to induce higher flow resistance in a specified direction. Chien et al. [16] fabricated two types of PHPs with 16 parallel channels. One of them had a uniform cross-section and the other one had 16 alternative cross section diameters. They claimed that the performance of both uniform and non-uniform PHPs increased with inclination angle but only the non-uniform type could be functional at the horizontal position. Additionally, Kwon and Kim [20] studied the effect of non-uniformity in the cross section of a PHP by testing a dual-diameter one-turn PHP. They made various types of PHPs with various inner diameters and observed operational characteristics of PHPs under different input powers and inclination angles. They recorded a 45% reduction in thermal resistance by using dual-diameter PHP. They also achieved an optimum range of diameter difference where thermal performance enhancement was maximized. Tseng et al. [15] proposed a novel design for dual-diameter PHPs in order to be functional even for top heat mode.

Other alternative techniques have been recently proposed by investigators in order to improve the flow motion in a preferential direction without altering the PHP's conventional shape. It has been shown that a non-symmetrical heating configuration at the evaporator of a single-turn [21] or multi-turn [22] PHPs can be a useful method to enhance the flow circulation and heat transfer, without precluding the intrinsic design simplicity of PHPs.

There are also some novel structural ideas in the literature for enhancing heat transfer in similar devices (e.g. thermosyphons) [23].

The presence of vapor bubbles has a significant effect on the displacement of the liquid slugs in PHPs. In other words, by the growth and shrinkage of vapor bubbles, the bulk of fluid is pumped within the tubes of a PHP. Using bubble pumps is not a new idea. Einstein's refrigerator [24] is among the first users of this phenomenon. Yuan and Prosperetti [25] simulated the flow induced by the bubble pump effect in a finite tube covered with a heating element joining two liquid reservoirs by a one-dimensional model. They included viscosity and surface tension effects in their model and showed that the system was capable of producing pumping action even in the presence of an adverse pressure gradient or while just a single bubble is present.

Nearly in all of the previous studies that attempts were made to improve the thermal performance of PHPs with geometrical modifications, using channels with different cross sections or check valves were used. The aim of this investigation is to exploit the bubble pump effect for creating a stronger circulation of the working fluid in a one-turn PHP. Hence, Attempts were made to enhance the circulation of the flow in the PHP by using an additional branch in the evaporator section as a secondary bubble pump and guiding the growth of the bubbles in one direction.

2. Experimental setup and procedure

Pictures relating to the experimental setups are shown in Fig. 1. Schematics of the PHPs, dimensions and thermocouple locations for both types of the pulsating heat pipes are depicted in Fig. 1 (a) and (b).