International Journal of Heat and Mass Transfer 126 (2018) 334–341

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Experimental analysis of the evaporation regimes of an axially grooved heat pipe at small tilt angles

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ARTICLE INFO

Article history:
Received 10 December 2017
Received in revised form 15 May 2018
Accepted 22 May 2018

Keywords:
Heat pipe
Evaporation
Groove
Capillary
Gravity

ABSTRACT

Using a high-speed digital microscope, visualization experiments of the vapor-liquid two-phase flow and heat transfer in an axially grooved heat pipe are conducted to investigate the evaporation regimes that occur at small tilt angles. The effects of the heat load and tilt angle on these evaporation regimes are analyzed. The evaporation regimes are further quantitatively characterized with a regime diagram developed based on the Bond number and Weber number. The results indicate that, unlike in a horizontal position, the evaporation regime of a grooved heat pipe with a small tilt angle can include corner-film evaporation induced by the combination of gravity and capillary force in addition to pool-surface evaporation and fin-film evaporation. Corner-film evaporation is the characteristic evaporation regime of an axially grooved heat pipe with a small tilt angle, and it exhibits random oscillatory motion of the vapor-liquid interface. Pool-surface evaporation is observed at small Weber numbers, corner-film evaporation occurs at large Weber numbers when the Bond number is approximately greater than 0.003, and fin-film evaporation occurs at medium Weber numbers.

1. Introduction

Owing to inherent advantages of simple structure, temperature uniformity, operational stability and non-moving parts, the axially grooved heat pipe has been widely used for the long-distance heat transport in a wide range of technical applications, such as waste heat recovery and utilization [1–3], high heat flux microelectronics cooling [4–6]. In some applications, limited space dictates that the axially grooved heat pipe works at a certain tilt. Differing from the horizontal mode, the driving force of an axially grooved heat pipe with a small tilt is no longer the capillary force. Instead, the combined effects of the capillary force and gravity are significant for the thermal behaviors, particularly for the evaporation phase change [7–9]. In addition, the overall thermal performance of a vapor-liquid phase change device depends largely on the evaporation regime in the evaporator section [10–12]. Therefore, it is of particular importance to understand the evaporation regimes of an axially grooved heat pipe with a small tilt.

Recently, several experimental and theoretical efforts to investigate the performance test [13,14], thermal analysis [15,16], geometry optimization [17,18], and engineering applications [19] of grooved heat pipe have been undertaken. However, these efforts mainly focused on steady-state performance analyses, such as the axial temperature distribution, effective thermal conductivity, and maximum heat transfer capacity. Because grooved heat pipes are typically made of metal materials, it is difficult to visually observe the capillary flow and phase change in heat pipe. Limited attempts have been made to visualize the vapor-liquid two-phase flow [20–22] in axially grooved heat pipes in order to reveal the mechanism of the evaporation phase change heat transfer. Wong et al. [20] visually analyzed the evolution of the two-phase interface in the evaporator section of heat pipe with a U-shaped groove, and observed a small pulse at the vapor-liquid interface in the evaporator section under high heat loads. In general, few attentions have been paid to the visualization of capillary flow and hence the evaporation regimes in microgrooves [23,24]. To elucidate the evaporation regimes in the evaporator section, visualization experiments are conducted with a high-speed microscopy imaging system to investigate the capillary flow and evaporation heat transfer inside grooves.

The thermal performance of a grooved heat pipe is significantly influenced by the tilt angle of the placement. In the horizontal

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.05.112
0017-9310/

state, the backflow of condensate liquid to the evaporator section is driven solely by the capillary force produced by the axial grooves, whereas gravity has no effect. At a large tilt (such as a vertical position), gravity dominates the vapor-liquid two-phase flow and phase change heat transfer in the axially grooved heat pipe, and the capillary force can be considered negligible. Given the importance of heat pipe placement, some attempts have been conducted to investigate the effect of gravity on the heat transfer characteristics of heat pipe with axial grooves. Liu et al. [9] studied the effect of tilt angles between 0° and 90° on the thermal performance of an axially-grooved heat pipe. Their results indicate that the inclination angle plays a significant role in the heat transfer performance of grooved heat pipes no matter what the water or the nanofluid as the working fluid, and the grooved heat pipe with inclination angle of 45° possesses the best thermal performance (heat transport capacity and thermal resistance) using both the nanofluid and water. Cao et al. [25] investigated the heat transfer performance of a copper-water axially grooved heat pipe in both horizontal and vertical state, and observed that the heat transfer limit in the vertical state is enhanced owing to the effect of gravity. These available studies, however, have primarily focused on heat transfer characteristics at a large tilt angle or in a horizontal state. Supowit et al. [7] investigated the heat transfer performance of an axially grooved heat pipe using IAS-based fluids at small tilts ranging from 3° to 6°, and pointed out that the tilt angle is of significance for the axial distribution of the liquid film. However, there have been few studies on evaporation regimes in the evaporator section at small tilt. In this special condition, the gravity and capillary force are both acting on an axially grooved heat pipe simultaneously. At present, it is unclear what effect the extra gravity induced by a tiny tilt in the heat pipe placement may have on the evaporation regime.

In summary, great theoretical and experimental investigations have been conducted to explore the thermal performance of the heat pipe with axially grooves (including the "Ω"-shaped, trapezoidal, rectangular and triangular grooves), especially the heat transport capability, thermal resistance, axial temperature distribution and groove optimization. However, the available studies in terms of axially grooved heat pipe pay little attention to the evaporation regimes at small tilt angles. The evaporation regimes largely determine the overall thermal performance, which is of significance to the performance optimization of heat pipe. In addition, a detailed understanding of heat transfer performance at the evaporator section requires a unified view of evaporation regimes of axially-grooved heat pipe. To obtain further insights into the evaporation regimes of grooved heat pipes with small tilt angles, experiments are conducted to investigate the vapor-liquid two-phase flow and phase-change heat transfer in a heat pipe using a visualization system with a high-speed CCD. The effects of the tilt angle and heat load on the evaporation regimes in the evaporator section are analyzed. Three typical evaporation regimes, including pool-surface evaporation, fin-film evaporation and corner-film evaporation, are visually identified in the evaporator section. These evaporation regimes are further quantitatively evaluated with a regime diagram based on the Bond number and Weber number.

2. Description of experiments

Experiments are performed using a visualization system to investigate the evaporation regimes in the evaporator section of an axially grooved heat pipe with small tilt angles. As illustrated in Fig. 1, the experimental setup consists of the axially grooved heat pipe, an electric heating unit, a cooling unit, a tilt adjustment unit, and monitoring devices.

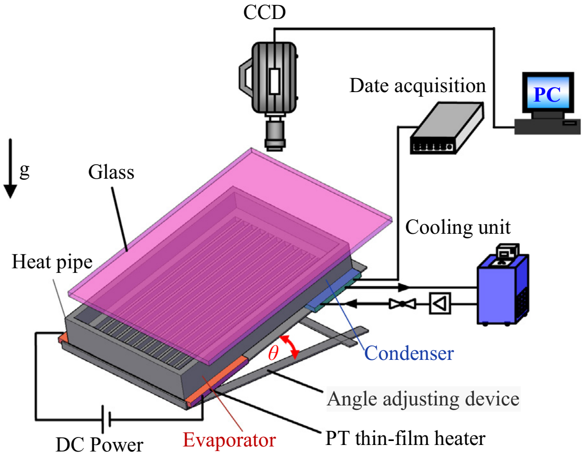

Fig. 1. Schematic of the experimental apparatus.

The axially grooved heat pipe is made by an aluminum base plate (length, L_1 = 80 mm; width, W_1 = 80 mm; thickness, 4.5 mm), and a series of parallel grooves (total number: N = 23) with rectangular cross-sections (depth: 0.5 mm, width: 0.5 mm) are milled on the aluminum plate. The lengths of the condenser, adiabatic, and evaporator sections are L_c = 15 mm, L_a = 9 mm, and L_e = 18 mm, respectively. The total length of the grooves is L = 42 mm. A vapor chamber with a height of 3 mm serves as the vapor flow space above the parallel grooves, as shown in Fig. 2. To observe the motion of the phase interface and hence determine the evaporation regimes, the vapor chamber is covered by glass with thickness of 6 mm. This glass is installed between the aluminum base plate and the cover plate (length, L_1 = 80 mm; width, W_1 = 80 mm; thickness, 4.5 mm). The contact area between the aluminum base plate and the glass are sealed with O-rings, and the aluminum base plate and cover plate are fixed with bolts around the heat pipe with axial grooves. At the initial experimental conditions, the fluid inside the heat pipe is saturated vapor-liquid two-phase, and the initial pressure only depends on the initial temperature, which is unrelated with the atmospheric condition.

The grooved heat pipe is evacuated with a vacuum pump (unit type: RVP-4) and then charged by ethanol as the working fluid. A proper filling ratio is required to ensure superior heat transfer performance in a heat pipe with axial grooves. Excessively high liquid filling rate causes the appearance of liquid block at the condensation section and hence weaken the condensation performance of the heat pipe. What's worse, it may lead to the failure of the meniscus's generation, thereby failing to achieve heat pipe's start-up work. If the liquid filling rate is too low, it is difficult to form capillary flow in the groove on a horizontal state, and then the heat pipe is unable to start up and enter a stable operation. In order to ensure the stable operation, the filling rate is generally between 1.1 and 1.3 [26,27], so in this experiment the filling rate of 1.2 is adopted for the axially grooved heat pipe. Note that the filling rate of axially grooved heat pipe is defined as the ratio of the liquid volume (at 20 °C) to the total groove volume. It is undeniable that the liquid filling rate has a great influence on the heat resistance and heat transfer capability of the grooved heat pipe. Within the stable work of the axially grooved heat pipe at small tilt angle, the liquid filling rate doesn't affect whether the evaporation regimes occurs or not.

In the experiment, the heat load is provided by an electric thin-film heater (length: 18 mm, width: 25 mm) attached to the evaporator section of the heat pipe, and adjustment of the heat load is achieved by modulating the DC voltage of the input power. Circulating water provided by a constant temperature water bath flows through the heat sink that is located on the back wall of the condenser section. The condenser releases heat to the circulating water, and its temperature can be controlled by