

重力效應對板式熱管性能之影響探討
Gravity Effect on the Thermal Performance of Flat Plate Heat Pipe (FPHP)

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摘要

本文針對「具毛細結構」及「無毛細結構」板式熱管於不同傾斜角下進行實驗測試。藉由不同操作角度，可獲得重力效應對於板式熱管之影響。實驗結果發現，在操作傾斜角-5°~+53°的範圍裡，板式熱管最大熱傳量會隨著傾斜角增加而變大。此外，我們在「無毛細結構」板式熱管觀察到溫度突降之現象，可定義此區域為沸騰起始區；對於「具毛細結構」板式熱管，根據其不同的熱流現象，我們亦將其熱阻曲線分為三種區域。
關鍵詞：熱管，傾斜角，重力效應

Abstract

This paper presents an experimental investigation of wickless and wick flat plate heat pipes (FPHPs) under different inclined angles. From different operating angles, the gravity effect on FPHP can be obtained. Experimental results showed that the maximum heat transfer rate of FPHPs becomes larger with the increasing of inclined angles (-5°~+53°). Additionally, temperature excursion phenomenon is observed on wickless FPHP; this can be defined as the boiling incipience zone. For wick FPHP, we classify the thermal resistance curves into three zones according to their different thermal behaviors.
Keywords: heat pipe, inclined angle, gravity effect

I. INTRODUCTION

Advanced packages and thermal management of high power electronics for space related program and commercial products require the use of high performance heat transfer devices. Heat pipe can provide sufficient cooling ability in these situations because of its high effective thermal conductivity by two or three orders of magnitude than copper. The development of heat pipe can be traced back to Gaugler [1]. Flat plat heat pipe (FPHP) is one type of heat pipes. It has some advantages over conventional heat pipes, such as geometry adaptation and nearly isothermal surface. Due to these advantages, FPHP has became attractive for some applications such as space vehicles [2] and electronic devices [3-4].

The working principle of heat pipe can be easily explained as the working fluid obtaining heat from the evaporator section by means of evaporating mechanism and releasing heat out of the condenser section by means of condensing. In general, there are five operating limits for heat pipe thermal performance, which include: capillary limit, entrainment limit, sonic limit, viscous limit and boiling limit [5]. Capillary limitation is usually the major factor that limits maximum heat transfer rate. For a heat pipe to operate continuously, the maximum capillary pressure must exceed the sum of overall pressure drop. Among different types of pressure drop, gravity effect is an important parameter.

In this paper, the gravity effect on wick and wickless FPHP have been experimentally studied by different operating angles.

II. EXPERIMENTAL SETUP

Figure 1 shows the schematic illustration of experimental setup, which consists of a FPHP with a heating block (30×30mm) in the evaporator section and a water-cooling chiller (60×30mm) in the condenser section. Bakelite is used as the clamping apparatus to reduce conductive heat loss. Temperatures in various locations of the system are measured by using T-type thermocouples. A static

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contact pressure about 12 kgw (1.3×10^5 Pa) between FPHP evaporator section and heater block is exerted. The whole apparatus is then placed in a low-pressure chamber in order to reduce convection effect. Water-cooling chiller is fixed at 20°C from -53 to 53 degree, and the experiments are conducted at selected inclined angles of –5, -2, 0, 2, 5, 10, 15, 20, 30, 45 and 53 degree. Design parameters and the prototype of FPHPs are shown in Table 1 and Figure 2.

The experimental procedure includes the gradual increase of heater power and the measurement of chiller inlet/outlet temperatures, chiller flow rate, and the temperature distribution of FPHP. The real-time data was monitored and the final data for each power input was recorded until the system reached the steady-state condition. Actual heat removal (Q_{act}, W) of FPHP is then calculated by using the temperature difference between the inlet and outlet of chiller:

$$Q_{act} = m\,C_p\,(T_{c,out} - T_{c,in}) \tag{1}$$

From equation (1), the overall thermal resistance (R_{th}, °C/W) can be obtained:

$$R_{th} = \frac{T_H - \dfrac{T_{c,in} + T_{c,out}}{2}}{Q_{act}} \tag{2}$$

Where

m : chiller flow rate (*ml/min*);

C_p : constant-pressure specific heat of water (*J/kg-K*);

T_H : heater surface temperature (°C);

$T_{c,in}$: chiller inlet temperature (°C);

$T_{c,out}$: chiller outlet temperature (°C).

III. EXPERIMENTAL RESULT

1. Error estimation

In the experimental process, many factors affect the final result, for example, FPHP fabrication error, system measurement error, and artificial error etc. In order to reduce these effects, experiments for all inclined angles are completed by using the same FPHP and the testing system assembly is never dismantled. Hence, the fabrication and artificial errors can be neglected and the major errors are from:

1-1. Data acquisition error: The total accuracy is ±0.3 °C for Agilent 34970A data acquisition unit and T-type thermocouple.

1-2. Chiller flow rate error: The chiller flow rate has re-tested for five times and its error is within ±2%.

2. Wickless FPHP

Wickless FPHP is just like a "thermosyphon." From the experimental result (Figure 3), dry-out phenomenon occurred under low heater power input when wickless FPHP is operated at horizontal condition. This is due to the lack of liquid capillary force. If wickless FPHP is operated at positive inclined angles (i.e. evaporator downward), its thermal performance becomes better obviously. This indicates that gravity is the main driving force in wickless FPHP. The test result also shows that with the increasing of inclined angle, dry-out phenomenon occurs later. When the inclined angle approximates to 53°, the maximum heat transfer rate can be close to 90W. Interestingly, for various inclined angles, the wickless FPHP presents temperature excursion for actual power at the range about 12~23W. Farsi et al. [6] also mentioned this physical phenomenon. The starting points of temperature excursions have no clear

Table 1　Design parameters of FPHPs

Item	Wickless FPHP	Wick FPHP
Material	6061-Al	6061-Al
Size (L×W×H, mm)	150x31x5	150x31x5
Working fluid	Acetone	Acetone
Wick width (μ m)	N/A	500
Weight (g)	55.97	26.6

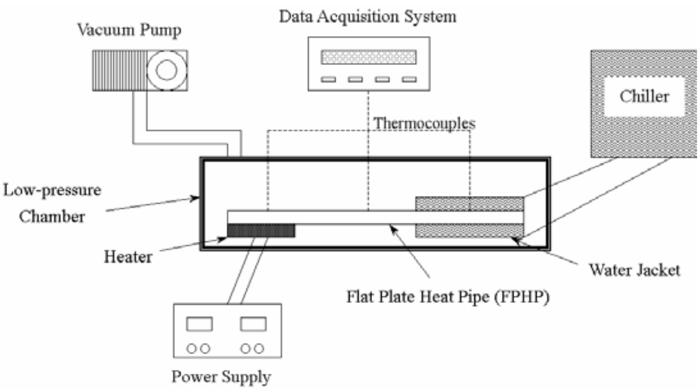

Fig. 1　Schematic of experimental setup

Fig. 2　Prototype of flat plate heat pipe (FPHP)

regularity with the inclined angles. These sections can be defined as the boiling incipience zone, total thermal resistance of wickless FPHP decreases to 0.5~0.6°C/W rapidly when the point of boiling incipience is surmounted. Furthermore, wickless FPHP without temperature excursion had ever been observed at small inclined angles (≦5°). The mechanism of excursion has to be correlated to the nucleation sites and the initial film thickness.

From Payakaruk et al. [7], they mentioned that the optimum operating inclined angles for conventional thermosyphon are between 40°~60°. This result corresponds to our research. We attempt to normalize the maximum heat transfer rate of the inclined FPHP. This is achieved by using the following equation:

$$f(\theta) = Q(inclined)/Q(53) \tag{3}$$

where *Q(inclined)* is the maximum heat transfer rate at a specific inclined angle, *Q(53)* is the maximum heat transfer rate at inclined angle equals 53°, θ is the operation inclined angle of FPHP.

By using this function, the trending plot for which Q's vary with the inclined angles can be obtained (Figure 4). There are two sections in this figure (*Slope I & Slope II*). For "*Slope I*" section, the maximum heat transfer rate raised obviously with the increasing of inclined angle. When the inclined angle is larger than 15°, this trending becomes alleviated. This may attribute to the physical properties of working fluid, gravity effect, the liquid-vapor counter-current flow phenomenon inside FPHP, etc.

3. Wick FPHP

For wick FPHP, the experimental result is shown in Figure 5. In the workable range of wick FPHP, heater temperature increases linearly but raised sharply when the dry-out point is reached. The maximum heat transfer rate increases with the increasing of inclined angle. On the contrary, when the FPHP is operated at -5°, the capillary force cannot sustain the gravity force and FPHP failed eventually. Figure 6 shows the thermal resistance curve for small inclined angles (-5° to +5°). From this figure, FPHPs present different thermal behaviors with the slight change

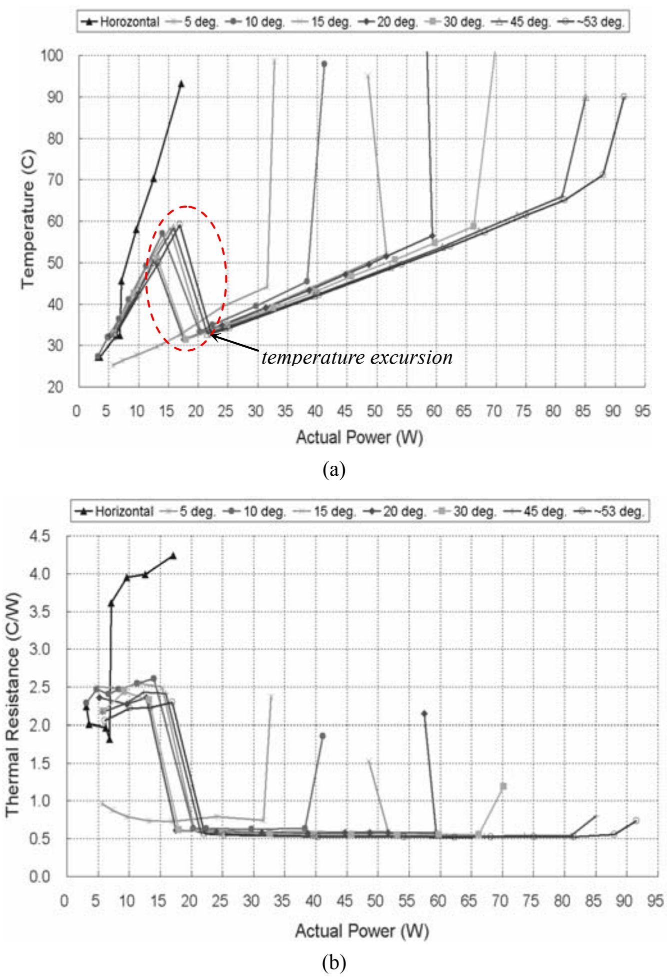

Fig. 3 Thermal performance of wickless FPHP at various inclined angles: (a) heater temperature; (b) thermal resistance

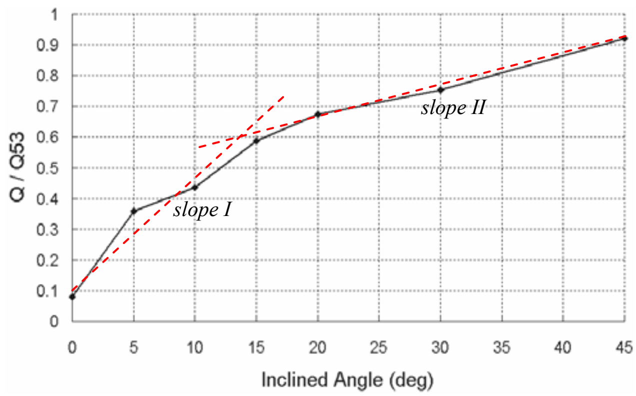

Fig. 4 Normalized maximum heat transfer rate of wickless FPHP at various inclined angles

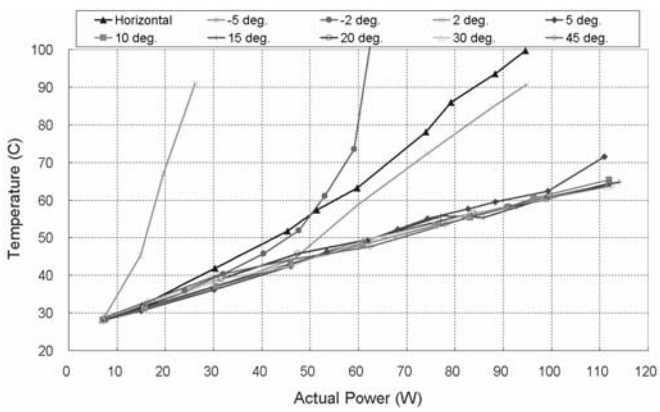

Fig. 5 Heater temperature of wick FPHP at various inclined angles

of inclined angles. This indicates that the thermal behavior of the wick structure of 500 μm width is very sensitive to gravity.

Figure7 shows the thermal resistance curve for all positive inclined angles (0^o to 45^o). Considering the thermal behavior, we classify these curves into three zones:

Zone I: Thermal resistances of FPHP are larger than 1.1 $^oC/W$ under low heater power for all positive inclined angles. We infer that the heat transfer mechanism of working fluid is pure convection and interfacial evaporation. At this time, the FPHP is not really "startup" yet.

Zone II: Thermal resistances for all positive inclined angles decrease rapidly. This may attribute to the boiling and condensing mechanisms inside FPHP. Interestingly, thermal resistance slightly decreases with the decreasing of positive inclined angle. We infer that there exists an optimum liquid film thickness on the wick surface. This phenomenon can be a reference for heat pipe design.

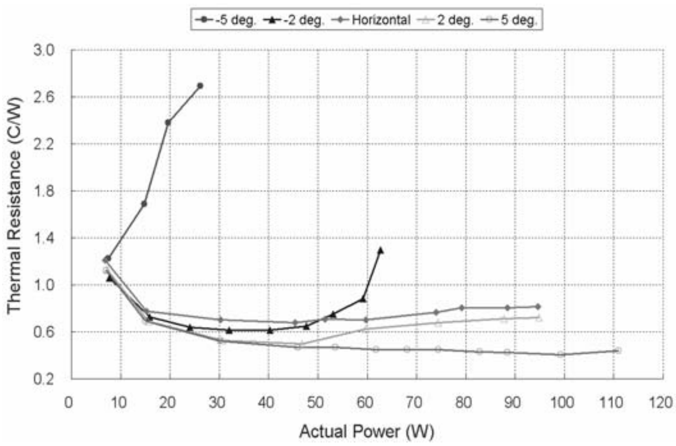

Fig. 6 Thermal Resistance of wick FPHP at small inclined angles

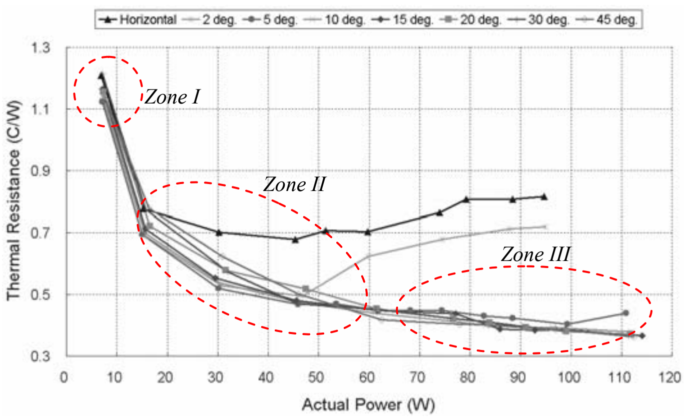

Fig. 7 Thermal resistance of wick FPHP at various inclined angles

Zone III: Thermal resistances for all positive inclined angles (0^o and 2^o are excluded because of the occurrence of dry-out) converge to a stable value of about 0.4 $^oC/W$. This may explain as the strong boiling and condensing circulation inside FPHP; the effect of liquid film thickness is therefore neglected.

Comparing wick FPHP with wickless FPHP, there are some similar and dissimilar thermal behaviors. For the similar thermal behavior, their maximum heat transfer rates increase with the increasing of positive inclined angle. For the dissimilar thermal behavior, wickless FPHP presents temperature excursion behavior under positive inclined angle condition. Moreover, the higher the positive inclined angle, the lower the thermal resistance. For wick FPHP, we do not observe obvious temperature excursion phenomenon. The trend of thermal resistance in "Zone II" seems to be contrary to that of the wickless FPHP.

IV. CONCLUSIONS

Based on the different operating angles of FPHPs, the gravity effect on the thermal performance of FPHP is studied and summarized as follows:

1. Within 53^o operating inclined angles, the maximum heat transfer rate of FPHP becomes larger with the increasing of inclined angle.
2. Under inclined conditions, wickless FPHP shows temperature excursion phenomenon. This can be defined as the boiling incipience zone. Thermal performance of wickless FPHP becomes better when the point of boiling incipience is surmounted.
3. Thermal resistance curve of wick FPHP can be divided into three zones. Zone I: interface evaporation mechanism dominates; Zone II: there exists an optimum liquid film thickness on wick surface; Zone III: strong boiling and condensing circulations occur.

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