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Experimental study on a novel loop heat pipe with both flat evaporator and boiling pool

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ABSTRACT

To further improve the stability and heat transfer efficiency of conventional loop heat pipe (LHP), a novel loop heat pipe with flat rectangular evaporator and boiling pool (NLHP) was designed and tested for electronic cooling in the present study, in which the main function of evaporator is to provide the capillary force for the loop while the boiling pool with an active heating area of 22 mm × 22 mm and a thickness of 15 mm is the main parts of heat dissipation. The porous wick of the evaporator is made of composite stainless steel meshes and methanol is used as working fluid. The results showed that the system could start up successfully when the heat load of boiling pool is higher than that of evaporator, and with increasing heat load of boiling pool, the NLHP has a shorter startup time and smaller temperature overshoot value. Another important factor influencing the startup is the time difference between the two heat supplies, and three modes were observed with increasing time difference. The highest temperature occurs at the bottom of boiling pool, and it rises with increasing heat load of evaporator as well as boiling pool. The maximum heat load of boiling pool is 200 W (heat flux 41.3 W/cm^2) while maintaining the heating wall temperature within allowable upper limit of 90 °C. A new equilibrium state could be established quickly when the heat load input changes, and temperature oscillation occurs hardly compared to the conventional LHP. The total thermal resistance increases with the increase of evaporator heat load, and decreases with increasing heat load of boiling pool. And the minimum thermal resistance of 0.07 °C/W is achieved at the heat load of 20–170 W for boiling pool.

1. Introduction

Heat dissipation has become a major factor that restricts the development of electronic systems to high power density and miniaturization as the rapid development of silicon technologies, and many kinds of cooling alternatives have been designed for the thermal management [1–3]. In comparison to convection heat transfer technologies, the phase-change heat transfer presents a better performance. A loop heat pipe (LHP) is a two-phase passive heat-transfer device which pumps the circulation of working fluid depending on the capillary force produced by the porous wick in evaporator. It not only possesses the main advantages of conventional heat pipe, but also provides additionally reliable operation over a long distance and different orientations in the gravity field as the improvement of capillary structure [4]. Since the LHP named "heat transfer apparatus" originally was patented in the USA in 1985 [5], it has achieved widely research recent years and got successful application in space engineering as well as electronic cooling. With increasing heat dissipation of electronic equipments, the LHP with flat evaporator tends to be the best candidate due to its greater interface, lower thermal resistance and easier contact with electronic microstructure.

Some characteristics are necessary for an effective LHP to cool high-powered and compact electronic devices, such as a higher capacity, smaller volume and lower thermal resistance. And lots of LHP with flat evaporator have been designed and researched successfully to meet these requirements. Singh et al. [6] developed a LHP with a flat disk shaped evaporator, 30 mm in diameter and 10 mm in thickness, with nickel wick and water as the working fluid, and the maximum heat load is 58 W (heat flux 8.2 W/cm^2) when the temperature of evaporator approaches to 90 °C. Nguyen et al. [7] demonstrated a copper–water LHP with a thickness of 15 mm, and the active heating area of circular flat evaporator is 3 cm × 3 cm. Consequently, the device shows a maximum capacity of 140 W (15.55 W/cm^2) and a minimum thermal resistance of 0.39 °C/W when the temperature does not exceed 80 °C. Chen et al. [8] proposed a LHP with steel biporous wicks and ammonia as the heat transfer agent. The stainless flat evaporator with

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Nomenclature

P	pressure, Pa
Q	heat load, W
R	thermal resistance, °C/W
T	temperature, °C
t	time difference, s
σ	the surface tension, N/m
r	the radius of curvature, m

Subscripts

bp	boiling pool
cond	condenser
cap	capillary
cc	compensation chamber
evap	evaporator
eff	effective
groove	groove
in	inlet
out	outlet
tot	total
fvap	the first vapor line
svap	the second vapor line
liq	liquid
w	wick
max	maximum
min	minimum

diameter of 43 mm and thickness of 15 mm can dissipate a maximum power reaching up to 130 W (12.8 W/cm^2) at the temperature below 60 °C, and keep the total thermal resistances of the system varying from 0.33 to 1.47 °C/W when the heat sink temperature is as low as −15 °C. Liu et al. [9] presented a flat type LHP with a diameter of 36.9 mm and thickness of 15 mm, in which biporous porous media and stainless steel mesh were adopted as primary wick and secondary wick respectively, the working fluid is methanol, and the highest capacity is 160 W (16.8 W/cm^2) with temperature below 85 °C. Choi et al. [10] displayed a high heat flux LHP of 28 W/cm^2 with sintered porous wick and water as working fluid, and the heat was rejected to a remote area at a distance of 500 mm while maintaining the operating temperature below 70 °C.

Temperature oscillation is another key factor in evaluating the performances of LHP, which is an outcome of the returning subcooled liquid temperature and the heat leak from evaporator to compensation chamber inside the system [11], and has a great influence on the stability and running life of electronic devices. This phenomenon has won widely research recent years [12]. As the LHP with flat evaporator has thinner porous wick than cylindrical one, more heat leak appears in the evaporator. As a result, a series of temperature fluctuations occur in the loop, and have been discovered and discussed widely in experiments [13–15]. Gai et al. [16] also observed the temperature oscillation in his study and divided them to three main types based on the previous research findings (i.e. low-amplitude and high-frequency, low-amplitude and long-cycle, high-amplitude).

Many new devices have been designed and tested to improve the performance of LHP too, such as loop heat pipe with multiple evaporators and condensers [17,18], anti-gravity loop heat pipe (AG-LHP) with a bubbler [19], loop heat pipe with a flat bifacial evaporator [20]. And there are still some problems requiring further study to improve the performances including higher heat flux, better stability, and so on. However, it is a very effective way to immerse the electronic chip into inert non-conducting liquid, which will evaporate and cool the electronic device with the latent heat of working fluid after heating. Wei et al. [21,22] found that the critical heat flux (CHF) reaches up to 80 W/cm^2 for the chip with micro-pin-fins in pool boiling, and 160 W/cm^2 in flow boiling, while the junction temperature is approximate to 85 °C. However, the driving force such as a pump is needed for running the flow boiling system, which is not convenient to install in small spaces of electronic devices and also makes some noises.

In this study, to further improve the heat transfer performance and the stability of LHP, a novel loop heat pipe with boiling pool (NLHP) is presented, which has a flat rectangular evaporator and boiling pool with an active area of 28 mm × 27 mm and 22 mm × 22 mm, respectively, and the characteristic thicknesses are 19 mm and 15 mm. The evaporator with double-layer composite porous wick is designed to produce capillary force for the system and the flat boiling pool is the very part connecting with electronics mainly for heat dissipation. The results show that the maximum heat load of boiling pool reaches up to 200 W (heat flux 41.3 W/cm^2) while the temperature does not exceed 90 °C, and no temperature oscillation was found in the loop.

2. Operation principle and thermodynamic processes of the NLHP

The designed experimental prototype of the NLHP is shown in Fig. 1, which mainly consists of a flat evaporator, a compensation chamber, a rectangular boiling pool, a condenser, a liquid line and two vapor lines. The operation principle of the system is as follows. The heat from the evaporator plate is transferred through the vapor grooves to the porous wick, a phase change occurs after the liquid reaching the saturated temperature and menisci are formed at the interface of porous wick and vapor removal channels, developing a capillary pressure as the only driving force to circulate the working fluid inside the loop. After the vapor–liquid mixture arrives at the boiling pool through the first vapor line, it is heated to saturated vapor first and then to superheated vapor by the heater in the boiling pool, and then is pushed into the condenser along the second vapor line driven by the capillary force. After sufficient heat exchanging in the condenser, the subcooled liquid flows back to the compensation chamber, keeping the evaporator at a lower temperature and supplying enough working fluid to the porous wick continuously. Because the heat exchanging of electronic device takes place mainly in the boiling pool, the function of evaporator is mainly to provide the driving force for the circulation of working fluid.

To better understand the thermodynamic processes of the NLHP steady operation, based on the operation principle as stated above, a *P*-*T* diagram is described as shown in Fig. 2 in accordance with traditional LHP thermal-hydraulic behaviors presented in Ref. [23]. The numbers in the diagram correspond to the physical locations illustrated in Fig. 1.

Located below the primary wick menisci in the evaporation zone, point 1 possesses the maximum pressure and is at a saturation state as working fluid evaporated partly. When the wet saturated vapor flows into the first vapor line (point 2) through vapor grooves and vapor collection groove, on one hand, the working fluid may be heated by the hot wall of evaporator, but the temperature does not increase due to its higher humidity; on the other hand, the pressure drop is small caused by the resistance loss in the process. Therefore, it changes slightly and