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Experimental investigation of pump-assisted capillary phase change loop

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HIGHLIGHTS

- A pump-assisted capillary phase change loop is presented.
- Both mechanical pump and capillary force are used for driving the working fluid.
- Test results show that no obvious temperature oscillation is observed.
- The loop can operate 17.7 W/cm^2 × 1850 mm at the heater surface temperature below 80 °C.
- Initial distribution of working fluid has impact on the operation characteristics.

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ABSTRACT

This paper presents an overview of a novel two-phase loop called "pump-assisted capillary phase change loop" designed to address the drawbacks of temperature oscillation and limited heat transfer distance in loop heat pipes. The proposed loop is a combination of active and passive systems. It is equipped with an evaporator designed in the type of flat-disk, and a biporous wick that provides the capillary force. In addition, methanol is chosen as the working fluid. During the heat-transfer process, the working fluid is transferred by both the capillary force and the driving force of the mechanical pumping. Both the sensitive and the latent heat of the working fluid are utilized to transfer heat. The liquid circulation through the compensation chamber takes away heat leak from the evaporator to the compensation chamber. Test results indicate that the system shows a very fast response to variable heat loads with no obvious temperature oscillation being detected. The maximum heat load the system could transfer increases up to 180 W (heat flux = 17.7 W/cm^2) with transport distance of 1850 mm at the heater surface temperature below 80 °C, when the power input of the mechanical pump is 2 W. The evaporator thermal resistance varies between 0.298 K/W and 0.196 K/W at the heat sink temperature of −10 °C.

1. Introduction

At present, cooling technologies are widely used in aerospace, energy, and other fields. Cooling technology could be divided into two broad categories—active and passive—based on the power source of the system. Active cooling systems, such as micro-channel and micro-jet loops, rely on a mechanical pump to drive the working fluid, while passive systems like loop heat pipe (LHP) and capillary pumped loop (CPL) use capillary force to transport heat. Both approaches have their advantages and disadvantages. Active systems are characterized by controllability and long transport distance. However, restricted to single-phase heat transfer, in order to dissipate high heat fluxes, they would suffer from a drastic pressure drop, resulting in extremely high power input of the mechanical pump. On the other hand, LHP is an efficient two-phase heat transfer device [1]. The capillary pump facilitates circulation of the working fluid [2]. The maximum heat load and transport distance of LHP are highly dependent on the capillary force. For a flat miniature LHP, the maximum heat load and transport distance sharply decrease [3–11]. For the LHP system with methanol as the working fluid, Liu et al. [10] have tested an LHP with the transport distance of 300 mm. The heat load reaches 160 W (heat flux 16.8 W/cm^2) when the evaporator wall temperature is below 85 °C. Li et al. [11] have developed an LHP with flat disc-shaped evaporator. The system reaches 100 W (heat flux 10.4 W/cm^2) at the evaporator wall temperature below 75 °C and the heat transport distance is 360 mm. Temperature oscillation, which is also observed in LHP, has a significant impact on the performance of the system.

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Nomenclature

P	pressure, Pa
Q	heat load, W
W	pumping power, W
T	temperature, °C
Subscripts	
V	vapor
l	liquid
sink	heat sink
pump	mechanical pump
Abbreviations	
Evap-out	evaporator outlet, T6
Wall	heater surface, T1~T4
CC-in	compensation chamber inlet, T19
CC-out	compensation chamber outlet, T17
CC-wall	compensation chamber wall, T5
Cond-#1 inlet	condenser #1 inlet, T10
Cond-#2 inlet	condenser #2 inlet, T11
Amb	ambient

Temperature oscillation in LHP is mainly caused by the liquid—vapor interface fluctuation inside the system [12–18]. J. Ku et al. [12,15] showed that loop operating temperature was dependent on the compensation chamber temperature. Both the returning subcooled liquid and the heat leak from the evaporator oscillating would cause the compensation chamber temperature to oscillate, leading to temperature oscillations in the rest of the loop. Mo [13] analyzed the test results and inferred that the position of the vapor—liquid interface inside the condenser varied with the temperature oscillations, resulting in liquid—vapor interface motion in the compensation chamber. Y. Chen et al. [14] studied a miniature LHP under varying heat sink temperatures, heat loads, and orientations. They deduced that the change of liquid—vapor distribution between compensation chamber, evaporator, and condenser caused the temperature oscillations. R. Singh et al. [16] proposed that the oscillation occurring in LHP was dependent on the thermal and hydrodynamic conditions inside the compensation chamber. Zhang et al. [17] found that the temperature oscillation in LHP occurred partly because of the restructuring of the phase distribution of the working fluid in the compensation chamber owing to heat leak from the evaporator to the compensation chamber. Gai [18] supposed that the vapor bubble condition inside the compensation chamber was mainly determined by the heat leak from the evaporator to the compensation chamber, the heat loss to the ambient, and the temperature and rate of sub-cooled liquid. The growth rate of the vapor bubble or dissipation inside the compensation chamber determined the nature of temperature oscillation.

In order to solve the problems of temperature oscillation and limited heat transport distance in LHP, a novel two-phase device called "pump-assisted capillary phase change loop" has been designed. The loop consists of an evaporator, a mechanical pump, a reservoir, an ejector, and a condenser. A schematic of the system is showed in Fig. 1. The loop is a combination of active and passive systems. Working fluid is transferred by both capillary force and mechanical pumping. The evaporator is the core component for absorbing waste heat of the electronic device. Both sensitive heat and latent heat of the working fluid are utilized to transfer heat. During the heat-transfer process, the mechanical pump forces liquid to circulate in the loop, thereby providing liquid for wick boiling and taking away heat leak from the evaporator to the compensation chamber. Hence, the vapor phase in the compensation chamber is restrained owing to the forced liquid circulation. The mechanical pumping in the loop significantly increases the liquid transport distance and improves the robustness of the system, while the porous wick prevents the liquid and vapor from penetrating. The separation of liquid and vapor flow into different lines helps prevent a large pressure drop, thus decreasing the pumping power.

In recent years, many researchers have experimentally studied the operating principles of pump-assisted capillary phase change loop [19–25]. It has been investigated for its potential to the thermal control of electronic devices [21]. These different types of systems show that pump-assisted capillary loop has many advantages, such as high heat flux dissipation and long transport distance [20]. Experimental results have shown that some parameters, including system pressure, liquid velocity, heat load, and heat sink temperature, have a significant impact on the operating temperature of the device [24,25]. There are some differences between the previous works and the loop proposed in this work. In the two-phase loop concept [19,21], the mechanical pump forces liquid

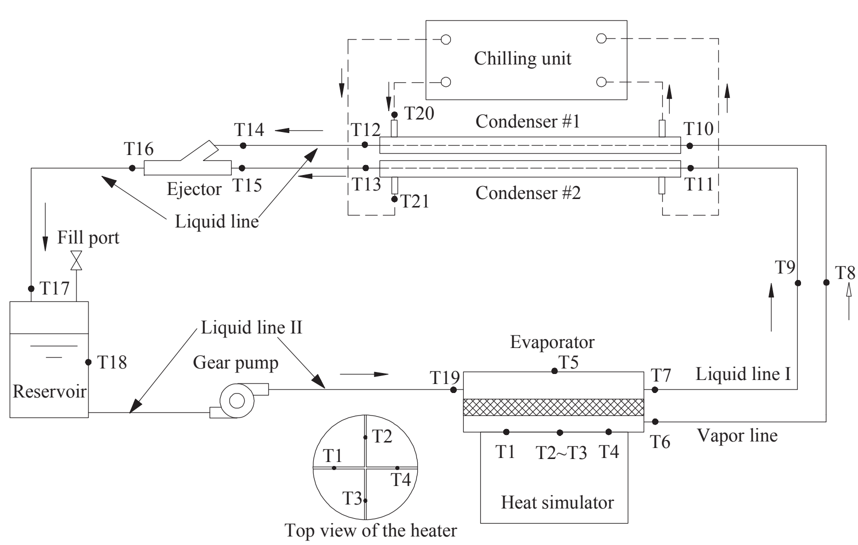

Fig. 1. Schematic of the pump-assisted capillary phase change loop and locations of the main thermocouples.