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Research Paper

Simulation of steady-state operation of an ejector-assisted loop heat pipe with a flat evaporator for application in electronic cooling

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HIGHLIGHTS

- An ejector-assisted loop heat pipe with a flat evaporator (ELHP) is proposed.
- The ejector is used to remove the generated vapor in the CC due to the heat leak.
- Performances of the ELHP and basic loop heat pipe (BLHP) are compared.
- Comparisons show that operating temperature of the ELHP is lower than that of the BLHP.
- Compared with the BLHP, the condenser length of ELHP can be decreased significantly.

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ABSTRACT

This paper proposes an ejector-assisted copper–water loop heat pipe with a flat evaporator (ELHP) for applications in electronic cooling. In the ELHP, the ejector is used to remove the generated vapor in the compensation chamber due to heat leaks through the wick, which could eliminate the need for the subcooling liquid supplied to the compensation chamber and improve the loop heat pipe performances. The steady-state performance of ELHP is simulated based on an established mathematical model and compared with the basic loop heat pipe with a flat evaporator (BLHP). The simulation results show that the operating temperature of the ELHP can be lower than that of the BLHP under the same heat load condition. Since the working fluid subcooling zone in the ELHP condenser is not required, the total length of the pipe-in-pipe type condenser also can be decreased by 24.4–34.8% when compared with that of the BLHP under given operating conditions. In addition, the effects of the thickness of the wick, the total length of the condenser, the inner diameter of the vapor line and the mass flow rate and inlet temperature of the cooling water on the performances of the ELHP are also evaluated in this study. These simulation results indicate that the ELHP can achieve a better performance than BLHP, which could be beneficial to the applications in electronic cooling.

1. Introduction

The rapid advance in electronic technology leads to increase the heat dissipation from the electronic devices [1]. Various cooling methods have been continuously employed to remove heat from the electronic devices. A loop heat pipes (LHP) is a suitable way for electronic cooling as it transports thermal energy over long distances, low thermal resistance and flexible transport pipe. Actually, LHPs are also highly efficient heat-transfer devices that can be applied in some thermal systems [2–4]. In a LHP, generally, the evaporator is its key component and uses the capillary action of inside wick to remove heat from a source and passively move it to a condenser [5]. Currently, the most typical evaporators used in LHPs are cylindrical and flat evaporators. Since most of the heat sources or objects that require cooling have a flat thermo-contact surface, such as the thermoelectric cooler (TEC), the flat evaporators can be suitable for these situations and draw more attention to researches in recent years [6]. In this case, many theoretical and experimental investigations have been performed by researchers to study various types of flat evaporator and different aspects of the flat evaporator LHP performance. Especially, many attempts have been made in developing wick design and configuration of the flat evaporator for LHP performance improvement.

Chen et al. [7,8] investigated the performance characteristics of two biporous wicks used in LHP with flat evaporator, and reported the LHP showed a very fast response to variable heat load and operated stably without obvious temperature oscillation. For the applications involving two-sided heat transfer of flat evaporator, Wukchul et al. [9] experimentally investigated a flat bifacial evaporator LHP and confirmed its operational reliability at all tested conditions. Li and Peterson [10] developed a quasi 3D model to study the heat and mass transfer in a square flat evaporator of a LHP with

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a fully saturated working fluid in wicking structure. Their simulations showed satisfactory accordance with the experimental results and obtained the local heat transfer mechanisms. Valery et al [11]. performed optimization of capillary structures for inverted meniscus evaporators of LHPs and proposed a methodology for selection of the capillary structure. Gian et al. [12] conducted experimental tests on the thermal characteristics of a loop heat pipe with flat evaporator, in which the wick is made of stainless steel. The results of experimental tests extend our knowledge of the stainless steel wick. Overall, investigating the LHP performance includes many different aspects such as working fluid, working temperature and pressure, compensation chamber, evaporator wick characteristics and design, etc.

In the flat type evaporator, the heat leak that passes from the heat source to the compensation chamber significantly affects the heat transport characteristics of a LHP. For example, the heat leak may lead to a higher minimum start-up heat load of the flat evaporator LHP compared with the conventional cylindrical evaporator LHPs [13]. Also, the heat leak could cause a temperature rise of the compensation chamber, which will induce the increase of thermal resistance [14]. In particular, the heat leak is usually compensated by subcooling from the returning liquid, increased heat leak to the compensation chamber may reduce the dissipated heat by evaporation at the wick surface and this leads to lower LHP performance. Thus, it is important to appropriately deal with the heat leak problem of the flat type evaporator. To reduce the heat leak, different methods have been utilized in flat or cylindrical type evaporators, including the addition of thermal resistance from evaporator to compensation through the wick structure or complex wick [15,16], the modification of evaporator [17] and the reduction in heat conduction of the evaporator casing [18]. Overall, the small heat leak can be achieved by using these methods. However, the effect of heat leak is still existed that could result in the degradation of the heat transport characteristics of the LHP. Therefore, alternative solutions need to be further developed for the designs of flat evaporator LHPs.

In this paper, we present an ejector-assisted copper–water LHP with a flat evaporator (ELHP) and a longitudinal compensation chamber (CC). By utilizing the ejector, the superheat vapor from the vapor grooves (primary fluid) can entrain the vapor (second flow) generated by the heat leak in the CC. In this case, there is no need to cool the working fluid to be the subcooling liquid at the outlet of the ELHP condenser. Thus, this configuration takes advantage of the higher heat transfer coefficient of working fluid in the two-phase zone than that in the subcooling zone of the condenser, and the ELHP can achieve better thermal performance than BLHP. In fact, ejectors have been widely used in various refrigeration and heat pump systems, such as ejector refrigeration systems, ejector enhanced heat pump systems, multistage and hybrid systems [19–22]. Therefore, it is a meaningful way to utilize an ejector to develop LHPs in this study. In the current work, a steady-state one-dimensional analytical model for ELHP is presented. Based on the model, a theoretical study is conducted to explore the effect of main parameters on the performance of the ELHP. Further analysis regarding the improvements achieved by ELHP is also discussed and compared with the performance of BLHP. The purpose of this paper is to contribute to the development of LHPs designed to solve the heat leak problem, and promote their applications in electronic cooling.

2. System description and analytical model

Fig. 1a shows the schematic diagram of ELHP. The ELHP consists of a flat evaporator with a wick and several vapor grooves, an ejector, a pipe-in-pipe type condenser, a compensation chamber, a control valve, and vapor line and liquid line. The ELHP loop includes a main working fluid circuit and a bypass working fluid circuit, which are combined by the ejector. In the main circuit, with the use of the ejector, the vapor generated by the heat load in the evaporator entrains the vapor generated by the heat leak in the CC through the bypass circuit. After the two fluids mix in the ejector, it passes though the vapor line and rejects the heat to the cooling water in the condenser together. The fluid at the outlet of the condenser then flows though the liquid line and finally enters into the CC. Note that theoretically, the required liquid subcooling at the CC inlet of the ELHP is not necessary because the generated vapor in the CC due to heat leaks can be removed by the ejector. In this case, the state of the fluid at the outlet of the condenser could be saturate or a little subcooling, which can enhance the condenser heat-transfer coefficient by main condensation heat transfer. Thus, the use of an ejector in the ELHP makes it possible to reduce the dimension of condenser, and increase stability and reliability of the ELHP [14]. Fig. 1b shows a P-T diagram of a working fluid cycle when the ELHP operates at a capillary controlled mode ($p_v > p_7$). In the main circuit, the saturate vapor is generated at the evaporating surface of the wick menisci (state 1); it becomes the superheated vapor (state $1'$) at the vapor groove outlet due to pressure losses; then the superheat vapor entrains the vapor from the CC (state 9) through the ejector; the mixed working vapor (state 2) passes though the vapor line and its pressure continues to drop along the way (state 2–3); by assuming that the vapor line is perfectly insulated, the vapor motion is considered close to isenthalpic and accompany with a slight temperature drop; the vapor releases its sensible and latent heat to the cooling water and results in a saturate liquid at the outlet of the condenser; Considering pressure losses in the ELHP condenser can be negligible [23], the process (3-4-5) of the working fluid is at constant pressure; the saturate liquid from the condenser passes though the liquid line (state 5–6) and become a two phase state (state 6) as the pressure of the working fluid decreases, whereas the temperature of the fluid slightly drops when assuming the liquid line is insulated completely as well; the generated vapor in the CC owing to the heat leak and the vapor of the return two phase fluid flows into the ejector through the control valve of bypass circuit (state 9), while the saturate liquid (state 7) in the CC is heated by the wick and losses pressure when flowing through the wick. This liquid has the lowest pressure in the system at the liquid side of the meniscus (state 8), right before evaporation takes place. The state 8 may be superheated, but boiling does not take place because it remains in such state for a too short time [24]. The superheat liquid is then evaporated across the meniscus and gains the lifted pressure, which is required as a pumping force to drive the whole system (state 8–1) from the wick. The whole cycle of the fluid flow is completed. It should be noted that the control valve in the bypass circuit is utilized to adjust the mass flow rate of vapor in the CC to make sure that the state of the fluid at the outlet of the condenser is saturate.

According to the working process of the ELHP, the following mathematical model for ELHP can be established based on the mass, momentum and energy conservations. The LHP is operated horizontal orientation that the evaporator and the condenser were located in one and the same horizontal plane. In this case, the effects of gravity on the ELHP can be ignored in this modeling. In addition, the widely used one-dimensional constant pressure mixing model of an ejector is employed in the simulation. In order to establish the model, the following specific assumptions are also made:

1. All components are assumed to be a steady-state and steady-flow process;
2. All components of the ELHP are thermally insulated using thermal insulation material;
3. Liquid/vapor interface locates at the interface between the wick and the vapor grooves (i.e. the outside of the wick).
4. State of the working fluid at the outlet of condenser (points 4, 5) is saturate;