Experimental Thermal and Fluid Science 62 (2015) 40–51

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Performance investigation of a compact loop heat pipe with parallel condensers

Ji Li [a,*], Lucang Lv [b]

[a] Laboratory of Advanced Thermal Management Technologies, College of Physics, University of Chinese Academy of Sciences, 19A Yu-quan-lu Road, Shijingshan District, Beijing 100049, PR China

[b] College of Physics, University of Chinese Academy of Sciences, 19A Yu-quan-lu Road, Shijingshan District, Beijing 100049, PR China

ARTICLE INFO

Article history:
Received 25 July 2014
Received in revised form 2 December 2014
Accepted 2 December 2014
Available online 10 December 2014

Keywords:
Loop heat pipe
Parallel condensers
Thermal performance
Condenser effectiveness

ABSTRACT

Two compact copper–water loop heat pipes (LHP) with flat plate evaporators were fabricated and tested in this study: one with a single condenser and the other with dual parallel condensers. A series of experiments were carried out to compare their heat transfer performance and operating behavior in stepwise heat loads with the assistance of an infrared thermographic technique. A maximum heating power of 1500 W (~100 W/cm^2) for the LHP with individual condenser and 1700 W (~120 W/cm^2) for the LHP with dual parallel condensers were obtained under forced air cooling condition when the vapor temperature in the evaporator was below 100 °C, and the corresponding total thermal resistance from the heating source to the ambient were 0.072 °C/W for the LHP with individual condenser and 0.067 °C/W for the LHP with dual parallel condensers, respectively. In addition, the uneven-distribution of working fluid into different condensers existed at comparatively low heat loads for the loop heat pipe with dual parallel condensers, which could bring forth deleterious consequences. Further visual investigations are needed to help better understanding the operation mechanism of the LHP with dual parallel condensers.

1. Introduction

Loop heat pipes (LHP) are well accepted as a high performance passive two phase heat transfer device in the field of thermal control of satellites and spacecrafts as well as cooling of electronics and computers [1]. Commonly, a loop heat pipe is composed of an evaporator, a condenser, a compensation chamber (CC), and vapor and liquid lines. Its evaporator is the key part directly connected to the heat source and contains the capillary wick providing the capillary force for the whole loop [2,3]. A loop heat pipe can efficiently transport a large heat load over a long distance with a small temperature difference. In addition, a loop heat pipe can work against gravity in some special conditions. Furthermore, the emergence of loop heat pipes with flat evaporator can transfer high heat flux loads easier than the LHPs with cylindrical evaporator to meet the demands of low thermal resistance [1–3].

The operating mechanism and performance characteristics of loop heat pipes are complicated, which are not fully understood so far. The main objectives of the recent works focused on the evaporator and compensation chamber design and analyzing the temperature oscillations during start-up and quasi-steady state process [2,3]. Moreover, the most concerned parameters for operation of a loop heat pipe are wick parameters, properties of working fluid, heat leak, gravity, sink and ambient temperatures, etc. For example, Zhang et al. [4] tested an ammonia-stainless steel LHP with nickel wick to study its start-up characteristics. It was found that both the heat leak from the evaporator to the compensation chamber and the pressure rise in the loop could increase the CC's temperature degree. Furthermore, the high heat load could reduce the start-up time of the loop heat pipe and the sink temperature did not affect the process much in practical conditions. The effect of distribution of a working fluid in a LHP on its operating temperature was described by Chernysheva et al. [5]. They theoretically compared the operating temperature under two operating modes of LHPs: absence of the working-fluid vapor phase in CC and presence of the working-fluid vapor phase in CC. Results showed that LHPs had a higher operating temperature in the latter mode.

Mo et al. [6] presented a copper–water loop heat pipe with flat evaporator and studied the gravity effects on its heat transfer characteristics experimentally. The innovation of the LHP design was that the evaporator and the CC were combined together with dimensions of 32 mm (L) × 32 mm (W) × 10 mm (H). A minimum thermal resistance about 0.2 K/W was achieved at the vertical orientation with a heat load of about 300 W. In addition, a temperature overshoot at low heat loads and oscillations at all heat loads

* Corresponding author. Tel.: +86 13522278866.
E-mail address: jili@ucas.ac.cn (J. Li).

http://dx.doi.org/10.1016/j.expthermflusci.2014.12.001
0894-1777/

Nomenclature

C	thermal capacity rate, W/K
c_p	specific heat, J/(kg K)
E	effectiveness
h_{fg}	latent heat of evaporation, J/kg
k	thermal conductivity, W/(m K)
$\dot{m}$	mass flow rate, kg/s
P	pressure, Pa
Q	total heat load
R	thermal resistance, °C/W
S	area, m^2
T	temperature, °C
x	vapor quality

Greek symbols

α	heat transfer coefficient, W/(m^2 K)
ν	kinetic viscosity, m^2/s
ρ	density, kg/m^3

Subscripts

a	ambient
c	condenser, cold
e	evaporator
g	gravity
h	hot
i	inlet
l	liquid
o	outlet
v	vapor
w	wick

were observed, and two methods to prevent large oscillations were recommended, namely, higher charging ratio and smaller pore diameter. Another copper–water loop heat pipe with a 80 mm(L) × 42 mm(W) × 7 mm(H) flat-oval evaporator was investigated by Maydanik et al. [7]. In the horizontal condition, a minimum thermal resistance of the LHP equal to 0.044 °C/W was obtained at the heat load of 1200 W. Wang et al [8] studied the effects of different condenser locations and operating orientations on the performance of a miniature loop heat pipe with an oval flat type evaporator.

In the above references, the condensers were all being cooled by running water over them with a low sink temperature. Recently, Li and his coworkers [9] fabricated a copper–water LHP with a finned tube condenser. In this way, natural convection or forced convection of air can be used to dissipate heat from the condenser. In the gravity assisted mode, the LHP was tested systematically and a heat flux more than 100 W/cm^2 and a thermal resistance as low as 0.033 °C/W were achieved at forced air cooling. It was also found that the condenser provided a large percentage contribution to the total thermal resistance of a loop heat pipe if using air cooling at the condenser side. Thus, it was speculated that a design of parallel condensers would help in reducing the total thermal resistance of a loop heat pipe.

However, the investigations on loop heat pipes with two or more condensers in parallel are few. Definitely, the heat and mass transfer processes for a LHP with parallel condensers are more complicated than one with single condenser. By using MEMS fabrication methods, Koveal [10] tested a plate type LHP with dual parallel condensers and a low thermal resistance of 0.05 °C/W was obtained. To cool down the TacSat-4 micro-satellite, Dussinger et al. [11] developed an aluminum/ammonia loop heat pipe thermal control system with parallel condensers for micro satellite to transport 700 W of heat and in aid to enhance the flow stability, a flow balancer was designed and installed. Nagano and Ku [12] conducted a comprehensive test to study the thermal performance of a LHP with two evaporators and two condensers. The start-up process, capillary limit, effects of gravity and heat loads were analyzed in detail.

All the above mentioned works with parallel condensers adopted similar configuration, in which the parallel condensers shared a vapor line and a liquid line connected to the evaporator. Actually, this kind of configuration is a quasi-parallel type (or pseudo-parallel type) and will cause a serious issue: the working fluid will interact with each other when flowing in and out of the condensers, which will result in unexpected interaction of working fluids before they return back to the evaporator and most worse, this kind of interaction may cause partial de-priming of the evaporator or sudden temperature overshoot in the evaporator. This unexpected consequence has been verified by the recent international TacSat-4 micro-satellite mission in 2012 [13].

Most recently, considering this shortcoming, Li et al. [14] developed a new type loop heat pipe with COMPLETE parallel condensers (or a PERFECT arrangement of parallel condensers without such flow interaction) and firstly applied this device to cool high power LED chips. As indicated by Li et al [14], a loop heat pipe with parallel condensers has many advantages in principle compared to one with single condenser: (1) higher heat transfer capacity even if the total heat transfer area of both LHPs are same; (2) lower thermal resistance due to reduction in flow resistance along the loops; (3) symmetric design to comply with special required arrangement; (4) more flexible and reliable in gravity environment. Coincidentally, Mo and his coworkers proposed a loop heat pipe with bi-transport loops (actually, a design with dual parallel condensers) for graphics processing unit (GPU) cooling [15]. A low thermal resistance of 0.17 °C/W from the evaporator to the cooling water was obtained with aid of gravity at a corresponding heat load of 380 W.

In the present work, two different copper–water LHPs are fabricated with a novel evaporator. The first LHP has single condenser and the second one has dual parallel condensers, but both the total external areas of their condensers are the same. Their detailed schematics are presented in the following section. The main objective of the present investigation is to evaluate the improvement of thermal performance of a loop heat pipe with parallel condensers over a loop heat pipe with single condenser in quantity, especially at high heat loads up to 2000 W (e.g., IGBT/laser/photovoltaic chip cooling). Meanwhile, the characteristics during start-up process and normal operation are analyzed, and the uneven distribution of working fluid in the condensers are explored and identified carefully. The results given in this study provide a fundamental pioneering data for the future investigations in this subject.

2. Fabrication of LHPs

As shown in Fig. 1, the LHP with single condenser has a flat square evaporator, a large cross-flow condenser, a vapor line and a liquid line; meanwhile, the LHP with dual parallel condensers has a flat square evaporator, two cross-flow condensers, two vapor lines and two liquid lines. Detailed geometric parameters of the LHPs are presented in Table 1. The evaporator has an active area