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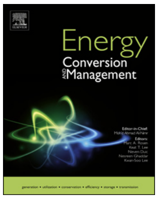

An investigation on optimal external cooling condition for an ultra-thin loop thermosyphon-based thermal management system

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ABSTRACT

Thermal management system plays a critical role in dissipating heat and guaranteeing the safety of facilities. Among the various thermal management technologies, thermosyphon receives increased attentions owing to the fast developing demands in high-efficient cooling technology. In this paper, the heat transfer performance of an air-cooling assisted thermal management system (AATM) with ultra-thin loop thermosyphon (UTLT) is investigated with experimental method and theoretical analysis. Specifically, the effects of the assisted cooling conditions including the placement of the condenser and the consumed fan power on the start-up characteristics, operating temperature and thermal resistance of the ULLT-based system are respectively discussed. During the experiments, conventional point measurement and IR thermography are both adopted to detect the temperature variation and capture the vapor-liquid interface formed in the loop pipeline of the UTLT. By revealing the movement of vapor-liquid interface under various cooling conditions, it is verified that there always exists an optimal cooling condition for the UTLT-based AATM to start up most quickly and operates with the highest efficiency. Simply raising the cooling capacity leads to the liquid stagnation in the pipeline and triggers adverse temperature excursion. A proper regulation on the coupled cooling condition could significantly improve the operational safety and reliability of the UTLT-based AATM. In the present work, the operating temperature of the UTLT under the optimal cooling condition can be decreased by 5.2 K and the thermal resistance can be reduced by 24.2% to only 0.169 K/W. In addition, an effective model to predict the thermal performance of the UTLT-based AATM has been established with 93.6% of the experimental data in the ± 15% error band.

1. Introduction

Along with the development of faster processor speeds and higher levels of integration in electronics, super-cooling schemes capable of dissipating high heat fluxes within a small temperature budget and limited space become the serious bottleneck in many applications, like power electronics, advanced batteries, laser diode three-dimensional, integrated chip architectures and so on [1,2]. As a promising technology for efficient cooling, looped two-phase devices display some unique merits, such as high heat transfer capacity, no external power consumption, long heat transfer distance and flexibility for installation. Hence, intensive attentions have been paid on the investigations of high-efficient looped two-phase devices coupled with other cooling technologies for passive thermal management system [3–6].

Usually, looped two-phase devices can be further divided into the loop heat pipe (LHP) with capillary core and the wickless loop thermosyphon. For the traditional LHP with capillary core inside the evaporator, a relatively high capillary limit to provide a powerful driving force and a respectively high porosity to ensure a low flow resistance are both required to guarantee the effective circulation of working fluid [7,8]. As for the two-phase loop thermosyphon, the driving force is usually determined by the density difference between the vapor-liquid phases [9].On account of the advantage of latent heat and the fast circulation of the two-phase flow inside the system, either LHP or loop thermosyphon presents satisfactory thermal performances, and is suitable for highly-efficient cooling. Pei et al. [10] studied a type of variable conductance loop thermosyphons (VCLT) filled with R134a as the working fluid. The experimental results illustrated the heat transfer performance of loop thermosyphons could be regulated with an effective adjustment mode, and the maximum ratio of heat transfer adjustment of their VCLT reached nearly 85%, and the lowest thermal resistance was as low as 0.0074 K/W. Ziapour et al. [11] proposed a kind of enhanced solar collector using the loop thermosyphon combined with photovoltaic cells, their simulation results indicated that the

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Nomenclature

A	nominal error range of an instrument
Cp	specific heat at constant pressure, J/kg·K^{-1}
D_h	hydraulic diameter of groove inside the evaporator, m
d	inner diameter of loop pipeline, m
E	measurement uncertainty
FR	filling ratio
$H_{f.g}$	latent heat of the working fluid, J/kg
H_f	height of the fin, m
h_a	heat transfer coefficient of air
I	current, A
i	sequence number of test
j	sequence number of variable
k	coverage factor
m_V/m_L	mass flow rate of vapor/liquid, kg/s
n	number of the channels
l''	length ratio of the vapor line, $=L_{v.l}/L_{loop}$
$L_{v.l}$	length of the vapor line, m
$L_{l.l}$	length of the liquid line, m
L_{tp}	length of the two-phase flow section, m
L_{loop}	length of the pipeline, m
P_f	fan power, W
ΔP_{drive}	driving pressure drop, Pa
ΔP_{loop}	pressure drop of loop pipeline, Pa
P	pressure drop, Pa
Pr	Prandtl number
Q_{in}	input heating load, W
R	thermal resistance of heat pipe, K/W
Re	Reynolds number
T_s	saturation temperature, K
$T_{e,aver.}/T_{c,aver.}$	average temperature of the evaporator /condenser, K
$T_{e,max}$	maximum temperature of the evaporator, K
$T_{e,entr.}/T_{e,exit.}$	temperature at the entrance/exit of the evaporator, K
T_L	liquid temperature at the outlet of the condenser, K
$t_{start\text{-}up}$	start-up response time, s
U	voltage, V
u_V/u_L	velocity of vapor/liquid, m/s
W_f	external work for effective cooling, W
X	Martinelli number
$x_e/x_{e,o}$	vapor quality/vapor quality at the outlet of the two-phase flow section
λ	frictional coefficient
λ_α	conductivity of air
ρ	density, kg/m^3
φ	heating efficiency of the system
Φ_L^2	amplification factor for two-phase flow
Θ	placed angle of UTLT, °
δ	thickness, m
Subscript	
Loop	loop pipeline
L	liquid
Tp	two-phase flow
V	vapor

thermal efficiency of the solar collector got significant improvement, the maximum tank water temperature could be sustained at about 72 °C even in the evening. Maydanik et al. [12] experimentally investigated a typical loop thermosyphon. Their experimental results indicated that the thermal resistance of the loop thermosyphon was only 0.03 K/W and the maximum transport heat reached nearly 100 W. They also pointed out that two-phase loop thermosyphon was capable for the thermal management system for fuel cells. Recently, Zhu et al. [13] come up with a horizontal two-phase loop thermosyphon (HLTS) for the application of solar parabolic trough receivers operating at 200–400 °C. The proposed HLTS-based receiver displayed an excellent heat transfer performance and enabled a minimal temperature drop between the absorber and the output, which caters to the requirements of commercial parabolic trough collector (PTC) systems.

So far, plenty of researches have been conducted to further improve the heat transfer capability of looped two-phase devices applied for thermal management system, nevertheless, the intensive researches mainly focus on the internal factors including the capillary core [14,15], filling ratio [16,17], evaporator geometry [18,19] and working fluid [20,21], *etc.* The investigations about the effect of external cooling condition on the thermal performance of the looped heat pipe are still quite fragmentary, not to mention revealing the influence on the coupled system.

Recently, Becker et al. [22] experimentally investigated the effect of the external factors including the orientations and coolant temperatures on the heat transfer characteristics of a LHP with a flat-oval evaporator. Their work not only verified the effect of orientations on the heat transfer performance of the LHP, but also revealed that the total thermal resistance of LHP was governed by the heat transfer at the condenser. Although the liquid-vapor interface inside the condenser was not precisely captured in their work, they still pointed out the fact that the condenser internal surface area used for condensation would increase with the raising of heat load, whatever the operating conditions.

Chernysheva et al. [23] discussed the effect of external factors including the device orientation, the cooling temperature and the heat exchange condition with the surroundings on the operating performances of LHP with a flat-oval evaporator. Their work clearly disclosed that the cooling condition had great influence on the thermal resistance as well as the evaporator temperature, especially under high input heat load. With a series of experiments, they concluded that the decrease in the heat-sink temperature would not result in an equivalent decrease of LHP operating temperature, or even become invalid to regulate the operation of the LHP.

Li et al. [24] proposed a type of LHP with dual parallel condensers for the cooling of high power LED illumination applications. Although an excellent thermal performance with total thermal resistance as low as 0.4 K/W was achieved under heating load of 300 W, the authors still put forward their concerns about that the instability would issue an unpredicable and non-uniform operation mode of the condensers. According to their inspired works, it was important to reveal the effect of

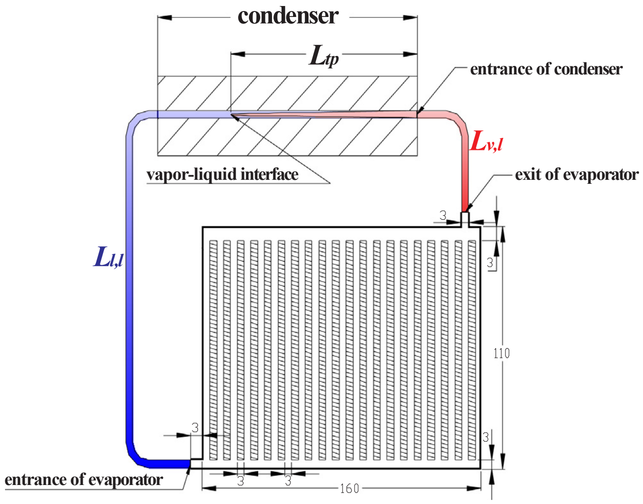

Fig. 1. Diagrammatic sketch of the UTLT.