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Research Paper

Experimental study of heat transfer and start-up of loop heat pipe with multiscale porous wicks

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HIGHLIGHTS

- A loop heat pipe with composite multiscale wicks was designed and investigated.
- Composite wicks can shorten start-up time and decrease start-up temperature.
- Achieve a synergy between thermal conductivity and thermal insulation.
- Nucleate boiling and film evaporation regions were observed.

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ABSTRACT

A loop heat pipe (LHP) with composite multiscale porous wicks was designed and investigated. The focus was on heat transfer and start-up characteristics. Three layers of wick were used to form the composite wicks. The primary layer was sintered on the evaporator wall using copper powder with different average particle diameters (d_p = 13, 37, 88, and 149 μm) to form a groove multiscale wick. The second layer was laid on top of the first one by a second sintering. The third layer was made of absorbent wool with excellent thermal insulation. A series of experiments were performed to study the effects of various parameters, including wick structures, tilt angles ($\theta = -90°$, 0°, and 90°), liquid filling ratios (38.5–64.1%), liquid line lengths, and heating power. Compared with conventional monoporous wicks, the composite multiscale porous wicks shortened the start-up time, decreased the wall temperature, and suppressed the temperature instability of the LHP. At a heat load of 200 W, the LHP with composite wicks could reach a heat flux of 40 W/cm^2 for the anti-gravity operation, under which the wall temperature was only 63 °C. Some reasons that accounted for performance improvement were as follows: the porous groove wall increased the surface area and multiscale structures realized a successful synergy between vapor release and liquid supply, large pores for vapor release, and small pores for liquid suction. In addition, a synergy between thermal conductivity and insulation was achieved, which ensured a high thermal conductivity for the primary layer wick and a good thermal insulation for the entire wick. This greatly reduced the heat leakage from the evaporator to the compensation chamber.

1. Introduction

With the development of science and technology, infrared detector arrays, solid lasers, high-performance microprocessors, and other optical/microelectronic chip devices are becoming smaller and more integrated. In these devices, a considerable amount of heat is produced within a small space, and it is difficult to dissipate this heat by natural or forced convection. Loop heat pipe (LHP), as a two-phase heat transfer device, plays a vital role in heat dissipation and has been widely used in energy applications, spacecraft, electronics device cooling, and commercial radiators [1,2]. After Gerasimov and Maydanik patented LHP in 1972 [3], many scholars have conducted a significant amount of research on LHP [4,5].

In LHP, porous wicks are the core components. They provide a capillary force for the circulation of the working fluid and a liquid flow path and place for the phase change heat transfer. Thus, the heat transfer and start-up characteristics of the LHP are closely related to the structures of porous wicks. So far, various wicks such as groove wicks [6], metal mesh wicks [7,8], polymer wicks [9,10], ceramics wicks [11], and metal powder sintered wicks (including

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Nomenclature

A	heater area on the wall, m^2
c_p	specific heat capacity, J/(kg K)
D_c	compensation chamber diameter, m
D_e	evaporator diameter, m
D_{ei}	wick layer diameter, m
d_e	effective pore diameter, m
d_p	particle diameter, m
ΔH	anti-gravity height, m
h	groove depth, m
L_l	liquid line length, m
m	mass flow rate, kg/s
p	groove wall width, m
Δp	pressure drop, Pa
Q	heat load, W
q	heat flux, W/cm^2
R	thermal resistance, K/W
r	latent heat vaporization, J/kg
T	temperature, K
t	time, s
w	groove width, m

Greek symbols

α	contact angle, °
β	heat leakage percentage
h	heat
δ	thickness of porous covers, m
ε	porosity of wick
ϕ	liquid filling ratio
μ	viscosity, kg/(m s)
θ	tilt angles of LHP, °
ρ	density, kg/m^3
σ	surface tension force, N/m

Subscripts

air	air
C	center wall of evaporator
Cin	condenser inlet
Cout	condenser outlet
cond	condenser
CP	compensation chamber
cpr	capillary pressure
CPin	compensation chamber inlet
C1~C4	location on condenser tube line
Eout	vapor outlet port
e	evaporator
f	flow
g	gravity
l	liquid
L	loop heat pipe
t	total
w	wick
V	vapor tube line
v	vapor
vap	vaporization
1~8	location on evaporator wall

stainless steel wicks [12], nickel wicks [13], and copper wicks [14]) have been studied and applied to the LHP [15].

However, the above mentioned studies mostly employ monoporous wicks, also called single-scale porous wicks. These wicks cannot handle high heat flux owing to the conflict between vapor release and liquid suction. According to Meléndez and Reyes [16],

$$m_v = \frac{\pi}{128}\left(\frac{\rho_v\sigma}{\mu_v}\right)\left(\frac{\varepsilon d_e^3}{\delta}\right) \quad (1)$$

where m_v is the mass flow rate of vapor; ρ_v, σ, μ_v, and ε are the vapor density, surface tension, viscosity, and porosity, respectively; δ is the wick thickness, and d_e is the effective pore diameter. Large mass flow rate of vapor requires large pore sizes to reduce resistance. However, according to the Laplace-Young equation, $\Delta p = 4\sigma\cos\alpha/d_e$ (α is the contact angle), small pores provide large capillary pressure for liquid suction. Vapor release and liquid suction require different pore sizes to achieve better heat performance in LHP. The best approach to solve this problem is to construct multiscale wicks, allowing different behaviors to correspond to different pore sizes. North et al. [17] sintered porous wicks with two pore sizes and reported film evaporation phenomenon in the wicks. The porous wicks satisfied the different requirements for vapor release and liquid suction. The porous wicks prevented the formation of a vapor blanket during the film evaporation process, and thus, the LHP exhibited good heat transfer performance. Semenic and Catton [18] investigated the heat performance of bi-porous wicks and found that thin bi-porous wicks can reach higher critical heat flux (CHF) than monoporous wicks. They showed that bi-porous wicks developed evaporating menisci not only on top surface of the wick but inside as well. The theory of vapor-liquid phase separation was used to explain the findings mentioned above. Yeh et al. [19] prepared bi-porous wicks by controlling the nickel particle diameters, pore former content, and sintering temperature. The results showed there was a clear and strong relationship between the effects of the pore former content and evaporative heat transfer of a bi-porous wick. The evaporative heat transfer coefficient of the bi-porous wick, which can reach a maximum value of 64,000 W/m^2 K, was approximately six times higher than that of the monoporous wick. Lin et al. [20] investigated the heat transfer of LHP with bi-porous and monoporous wicks, through experiments and simulations, and developed a new mathematical model for evaporation heat transfer. The results showed that a bi-disperse wick could decrease the thickness of the vapor blanket region to reach higher heat performance as compared to a monoporous wick. Recently, Li et al. [21] sintered nickel porous wicks and investigated the effects of sintering methods, proportion of pore former, and sintering temperature. Results showed that the optimal wicks sintered at 700 °C, using a cold pressing sintering method, with 30% pore former content by volume. Results also indicated that an LHP with bi-porous wick can start up and run reliably under different heat loads. Although the above studies involved bi-porous wicks, the vapor channel wall was mostly solid. The vapor and liquid can be separated in the vapor channel; however, the separation is not remarkable in the phase change region. To promote vapor-liquid phase separation, sintered porous wicks need to be used to build the vapor channels. Thus, the vapor can enter the channels immediately after evaporation, and porous wicks can supply the liquid sufficiently. Wu et al. [22] and Min et al. [23] validated this mechanism in pool boiling experiments. Ji et al. [24] experimentally found that porous wicks with different pore sizes could effectively separate the flow paths of the vapor and liquid, thereby achieving synergy among different pore sizes. The CHF can reach 3.7 times that on the plain surface.

The start-up of LHP is a complex transient phenomenon, affected by the vapor-liquid phase distribution, structural parameters of wicks, and working conditions. Singh et al. [25] investigated the start-up process of the LHP. At low heat loads, thermal and