



Thermal performance of loop heat pipes with smooth and rough porous copper fiber sintered sheets



Weisong Ling^a, Wei Zhou^{a,*}, Wei Yu^a, Ruiliang Liu^a, K.S. Hui^b

^a Department of Mechanical and Electrical Engineering, Xiamen University, Xiamen 361005, China

^b School of Mathematics, Faculty of Science, University of East Anglia, Norwich NR4 7TJ, United Kingdom

ARTICLE INFO

Keywords:

Loop heat pipe
Porous copper fiber sintered sheet
Surface morphology
Capillary pumping amount
Thermal performance

ABSTRACT

Smooth and rough porous copper fiber sintered sheets, employed here as wicks for loop heat pipes for the first time, were fabricated using a low-temperature solid-phase sintering method. The capillary performance of these porous copper fiber sintered sheets were analyzed and discussed. The influence of the surface morphology, filling ratio, and working fluid on the thermal resistance, evaporator wall temperature, and start-up time of the loop heat pipes were investigated. The results showed that the capillary pumping amount of working fluid for both smooth and rough porous copper fiber sintered sheets initially increases rapidly, and then gradually attains a stable state. The curve of the capillary pumping amount of working fluid can be described as a function that increases exponentially over time. When rough porous copper fiber sintered sheets are used as wicks and deionized water is used as the working fluid, the capillary pumping amount is maximized. Compared to smooth porous copper fiber sintered sheets, loop heat pipes with rough porous copper fiber sintered sheets exhibit a shorter start-up time, lower thermal resistance, and lower evaporator wall temperature. For a filling ratio in the range of 15–45%, loop heat pipes with rough porous copper fiber sintered sheets and a 30% filling ratio show lower thermal resistance and a lower evaporator wall temperature. Ultimately, the use of deionized water as the working fluid with a 30% filling ratio enables loop heat pipes with rough porous copper fiber sintered sheets to be stably operated at a heat load of 200 W.

1. Introduction

A loop heat pipe (LHP) is a highly efficient heat-transfer device that was initially proposed by scientists from the former Soviet Union in 1972 [1]. An LHP typically includes an evaporator, a condenser, steam and liquid lines, and working fluid as its main components. Further, an LHP exhibits excellent heat transfer performance with a steam-liquid phase change and has been widely used in many applications. For example, LHP without using the wick structure have developed to solve the problem of the high temperature and low efficiency of solar cells [2]. In the nuclear power field, a LHP have been designed for nuclear reactor power systems [3]. Especially, a mechanical pumped LHP can be also used for the aerospace industries [4]. Because the steam and liquid are separated and transferred through different pipelines [5], a reduction in the heat transfer efficiency caused by the entrainment limit [6] can be prevented efficiently. Thus, many new types of LHPs with different liquid-steam separators have been developed to improve the thermal performance by the experimental testing [7] and theoretical analyses [8]. As one of the most important parts of an LHP, the porous

wick provides a capillary pumping force to drive the circulation flow of working fluid [9]. However, the porous wick should possess a lower flow resistance and larger permeability to establish a flow channel for the liquid fluid [10].

The wick structure has a great influence on the capillary pumping performance of an LHP. In fact, many researchers have devoted considerable efforts to optimize and enhance the capillary performance of porous wicks [11]. Previous studies found that micro-groove wicks with simple structures are easy to fabricate [12]. However, the capillary force is insufficient because of the larger average size of these wicks and the limits in terms of their direction selectivity. Subsequently, multi-layer mesh wicks were developed to solve the problem of direction selectivity, but the capillary force remained insufficient for the increasing heat flux of electronic chips [13]. In recent years, many researchers have focused on sintered wicks. Sintered powder wicks, with effective three-dimensional network and fine pore structures, have been widely used in LHPs [14]. For example, Wu et al. [15] developed a novel sintered nickel powder wick for application in LHPs. The results showed that the thermal resistance of the LHP was as low as 0.095 °C/

* Corresponding author.

E-mail address: weizhou@xmu.edu.cn (W. Zhou).

Nomenclature		LHP	loop heat pipe
		PCFSS	porous copper fiber sintered sheets
		Subscripts	
A	area, m^2	amb	ambient
FR	filling ratio, %	cap	capillary
D	diameter, m	$cond$	condenser
H	height, m	cro	cross-sectional
K	permeability, m^2	eva	evaporator
K'	relative permeability, $\text{m}^2\text{-s/kg}$	ec	evaporator and condenser
L	length, m	ed	equivalent diameter
M	capillary pumping amount, g	ep	equivalent diameter of pore
N	number	eff	effective
P	pressure, Pa	l	liquid
ΔP	pressure difference, Pa	s	Steam
Q	heat load, W	$s.line$	steam line
Q_{FL}	filled-liquid mass limit, kg	$l.line$	liquid line
R	thermal resistance, $^{\circ}\text{C/W}$	w	wick
S	suppositional area, m^2	CC	compensation chamber
T	temperature, $^{\circ}\text{C}$		
ΔT	temperature difference, $^{\circ}\text{C}$	Greek symbols	
V	volume, m^3	μ	dynamic viscosity, Pa-s
V_{FL}	filled-liquid volume limit, m^3	ε	porosity, %
g	gravitational acceleration, m/s^2	ρ	density, kg/m^3
h	heat transfer coefficient, $\text{W/(m}^2\text{K)}$	τ	time constant, s
h_{fg}	latent heat, kJ/kg	η	kinematic viscosity, m^2/s
m	quality, kg	σ	surface tension, N/m
q	heat flux, W/m^2	θ	contact angle, $^{\circ}$
r	radius, m	φ	fiber volume fraction, %
x	constant coefficient about wick		
t	time, s		
y_0	maximum capillary pumping amount, g		
Abbreviations			
SEM	scanning electron microscope		

W, and the evaporator heat transfer coefficient was measured as $131 \text{ kW}/(\text{m}^2\text{K})$. Zhang et al. [16] investigated the effects of the sintering parameters on the porosity, pore size, permeability, and capillary pumping rate of wicks with nickel and nickel-copper powder, and the influence of the sintering time and temperature was also observed to be significant. Li et al. [17] developed two kinds of wick structures, i.e., single-powder (SP) and continuous step-graded (CSG) wicks, for LHPs. The heat transfer performance of the LHP with a continuous step-graded wick was found to be much higher than that of a single-powder wick.

The contradiction between the capillary pumping force and permeability of wicks has led to the development of innovative bi-porous wick structures [18]. These wicks usually possess two different pore sizes and intertexture each other. The smaller pore size provides the capillary force that drives the flow of the liquid working fluid, whereas the larger pore size establishes the flow channel for the liquid working fluid. Chen et al. [19] fabricated a sintered nickel powder bi-porous wick for a plate-type evaporator in an LHP. The results showed that the LHP had a heat load of 130 W with an evaporator wall temperature of 60°C , and a thermal resistance of $1.42\text{--}0.33^{\circ}\text{C/W}$ with a heat load of $10\text{--}130 \text{ W}$. Li et al. [20] proposed cold pressing sintering and loose powder sintering methods to fabricate nickel powder bi-porous wicks. The maximum porosity and permeability of these wicks could reach 77.4% and $3.15 \times 10^{-13} \text{ m}^2$, respectively. A previous study proposed the use of multi-layer metal foams and composite porous copper fiber sintered sheets as wick structures for LHPs. Improved heat transfer performance was observed for the LHPs with different heat loads [21–22].

Recently, many researchers carried out numerous research studies

to investigate performance parameters such as the capillary pumping force of the wick in LHPs. Nishikawara et al. [23] studied the effect of introducing gaps between the wick and evaporator wall on the heat transfer performance using numerical simulation methods. The results showed that the optimum gap enhanced the heat transfer performance when a wick with a low thermal conductivity coefficient was selected. Liu et al. [24] developed two sintered nickel powder wicks embedded in the evaporator of LHPs. With a heat load range of $10\text{--}170 \text{ W}$, the LHPs could successfully start up with the evaporator wall temperature below 90°C . Cheng et al. [25] investigated the capillary pumping performance of a porous wick in an LHP by developing a method that studied real-time changes in the curve of the capillary pumping amount. The results showed that the real-time changes in the curve of the capillary pumping amount recorded by an electronic balance and a computer could be described by an exponentially increasing equation.

Prior research focused on the structural designs, fabrication methods, and improvements in the heat transfer performance of the porous wicks in LHPs. The effects of the surface morphology on the thermal performance of LHPs have not been reported in the literature. In this study, both smooth and rough porous copper fiber sintered sheets (PCFSSs), which were employed as wicks, were fabricated using the low-temperature solid-phase sintering method for LHPs. The capillary pumping performance of smooth and rough PCFSSs was tested and analyzed. Furthermore, the influences of the surface morphology, filling ratio, and working fluid on the thermal resistance, evaporator wall temperature, and start-up time of LHPs were investigated in detail.

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