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Effects of multiple sintering parameters on the thermal performance of bi-porous nickel wicks in Loop Heat Pipes

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ABSTRACT

The thermal performances of a bi-porous nickel wicks in Loop Heat Pipe (LHP) including porosity, permeability, capillary pumping head and effective thermal conductivity (ETC) have been examined theoretically and experimentally, based on five key sintering parameters including the content of pore forming agent, compacting pressure, sintering holding time, sintering temperature and the particle size of pore forming agent. Firstly, a total number of 16 orthogonal tests are carried out with five key sintering factors and four levels of each factor. The optimal level of five sintering factors is obtained from the point of acquiring the most desirable overall performance of bi-porous nickel wicks, which can be used as the reference sintering process for bi-porous nickel wicks. Then, the experimental values of ETC were compared with eleven theoretical models. The results showed that the Alexander model and the Maxwell model overestimated and underestimated the experimental results of bi-porous nickel wicks, respectively. In the porosity range of 0.5–0.7, an average of the Chernysheva and Maydanik model and the Chaudhary and Bhandari model was found to be the best fit to the experimental data, providing an accurate method to predict ETC values of bi-porous nickel wicks of LHP.

1. Introduction

Loop Heat Pipe (LHP) is a high-efficient two-phase closed-cycle heat transfer system using capillary pumping principles. Porous wick is the key component in LHP evaporator by providing the driving force for circulation of the working fluid. With recent research and developments of compact LHP, new structures of porous wicks are increasingly being adopted to cope with highly intense heat flux used in high performance LHP. When heat flux is above 300 W/cm^2, conventional mono-porous wick cannot cope with the intense boiling and vapor–liquid interactions at the wicks outer diameter and vapor groove and will cause system failure by having a dry-out wick. To solve the problem, bi-disperse/bi-porous wicks have been developed for LHP evaporators due to their superior performance: there are two size pore scales distribution with the large pores providing quicker escape path of vapor at high heating load, and with the small pores improving the capillary pumping to facilitate the working liquid to circulate to nucleation sites and increase the menisci area for evaporation.

Two commonly used dual-pore structures in LHP evaporator are the metal powder sintering type and the silicon lithography type. The former is usually used in cylinder evaporators while the latter is for plate type evaporators. Based on pore forming method, the metal powder sintering type can be subdivided into bi-porous structure and bi-dispersed structure. Although bi-porous/bi-dispersed wick are commonly considered to have better heat transfer performance than mono-porous wicks in the research field of two-phase heat transfer, the research works on manufacturing process of bi-porous wicks/bi-dispersed wicks are lacking. To the best knowledge of the authors, there are mainly two manufacturing methods of dual-pore scale porous wicks for LHP cylinder evaporator. The first method is to sinter metal powder clusters directly, so the key problem is to fabricate clusters. Normally two ways, one is using bonder, that is, the macro-level cluster is formed by agglomeration of micro-level particles, where the large pores are formed by heating the cluster binders to decomposition while the small pores are formed by sintering powder particles. Detailed information of the bi-dispersed structure manufacturing process was provided by Lin et al. [1]. Determination of key thermo-physical parameters of the bi-dispersed structure was studied [2–4] and the evaporative/boiling heat transfer and two-phase flow characteristics were investigated [5–7]. Another way is sintering thin mono-porous layers then ground into clusters (such as Refs. [8,9] mentioned, but not involving detailed manufacturing process). The dual-pore scale wicks using the above method are

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Nomenclature

A	sectional area (m^2)
CC	compensation chamber
D	cluster size (m)
d	particle diameter (m)
E	compacting pressure(Pa)
F	pore former particle size (m)
G	sintering temperature(°C)
h/H	capillary pumping head (m)
I	sintering holding time (s)
J	content of pore forming agent (g)
K	permeability (m^2)
k_{eff}/ETC	effective thermal conductivity (W/(m K))
k_f	fluid thermal conductivity (W/(m K))
k_s	solid thermal conductivity (W/(m K))
m	mass (kg)
R_{eff}	effective pore radius (μm)
R	sensitivity
t	time (s)
T	temperature (°C)

Greek symbols

ε	porosity
θ	contact angle (rad)
μ	dynamic viscosity (kg/(m s))
ρ	density (kg/m^3)
σ	surface tension coefficient (kg/m^2)

Subscripts and superscripts

bi	bi-porous/bi-disperse
eff	effective
i	level No.
j	factor No.
mono	mono-porous
w	wick

called bi-dispersed wicks. The second method is using pore-forming agent (PFA). One kind of PFA can be volatilized during sintering (such as PMMA in Ref. [10]). Another kind of PFA is water-dissolved pore-forming agent (such as NaCl, Na_2CO_3 in Refs. [11–13]). The dual-pore scale wicks using this method are called bi-porous wicks. The large pores of bi-porous wicks are created by eliminating the pore forming agent in sintered wick while small pores are formed by sintering powder particle. According to the literatures mentions above, many research works are using PFA in bi-porous wick manufacture for basic experimental research, although there is still a long way to go before the large scale industrialized applications become viable. Due to the higher porosity and easier control of the size of large pores than those passively formed large pores in the bi-dispersed wick, the bi-porous wick is widely used in LHP and will be thoroughly investigated in the current study.

There are four key performance parameters for the bi-porous wick in LHP: porosity, permeability, capillary pumping head and effective thermal conductivity (ETC, k_{eff}). These parameters are strongly dependent on the metal powder sintering, which is a complex process affected by multiple factors. Yeh et al. [14] described the manufacturing procedures of bi-porous wick and made statistical experimental analysis of three fabrication factors which affect the heat transfer capacity with two levels each factor, which are particle size and volume content of pore forming agent, and sintering temperature. They found better heat transfer performances in their test ranges with higher volume content and smaller particle size of pore forming agent and higher sintering temperature.

From the heat flow network of LHP evaporator, the heat applied to the evaporator wall mostly evaporates the liquid inside, but the rest inevitably heats the liquid in compensation chamber (CC) through the CC wall and porous wick skeleton by heat conduction, which is called heat leakage --a troublesome problem causing LHP operation instability: temperature fluctuation, temperature hysteresis and even the wick dry-out. Heat leakage, to a great extent, depends on the ETC values of the porous wick used. ETC also indicates the thermo-hydraulic performance of LHP evaporator and CC – key to the capillary wick structure optimization, and its value is strongly related to porosity and permeability. Computation the ETC of porous wicks therefore becomes of great importance to analyze the LHP heat transfer performance and design optimal wick structure. A wide range of thermal conduction models have been developed to predict the ETC of two phase system through solid thermal conductivities (k_s), fluid thermal conductivities (k_f) and porosity (ε). Tavman [15] reviewed a few heat conduction models of porous media. The well-known models are the weighted arithmetic mean (heat transfer in parallel) and weighted harmonic mean (heat transfer in series) of two phase thermal conductivities, which are normally used to determine the upper and lower bounds of porous medium ETC but can often be inaccurate. Other advanced ETC models such as Maxwell–Eucken model [16], Krupiczka model [17], Woodside and Messmer model [18], Assard model [19], Chaudhary and Bhandari model [20], Alexander model [21], EMT model [22], Dunn and Reay model [23], are often used to predict the ETC of mono-porous wicks. However, there exist very few previous studies on evaluating existing ETC models for bi-porous wick and examining their prediction errors. In addition, the ETC models for LHP bi-porous wicks are very few. Semenic et al. [24] provided the relationship between thermal conductivity of bi-dispersed sintered copper wick and the diameter ratio of particles to clusters; however, their results strongly depended on the test samples. Chernysheva and Maydanik [25] reported a correlation but it was only aimed for bi-porous copper wick.

From the literature review, existing research on effects of sintering factors on bi-porous wick performance has only provided a qualitative analysis with a few factors and low levels for each factor. The majority of the current ETC models aims for the mono-porous wick. The two relations for bi-porous wick are based on the sintered copper powder without considering other materials. The current research aims to investigate the effect of multiple sintering parameters on bi-porous nickel wick performance including structure, fluid flow and heat transfer, to comprehensively analyze five sintering parameters (each with four levels), which are recognized as the main influence factors by existing researches, to study the influencing degree of each sintering parameter on porosity, permeability, capillary pumping head, effective thermal conductivity by an orthogonal experiment, and to find out the ideal sintering process of bi-porous nickel wick composing of optimal level of five sintering parameters. To examine the existing eleven ETC models for bi-porous nickel wick, comparison was made between the experimental and calculated values to provide a feasible and handy method for estimation of the effective thermal conductivity of bi-porous nickel wick.

2. Experiment

The bi-porous wick samples were fabricated by sintering the nickel powder INCO T255 with the filamentary microstructure,