Sintered Metal Wicks Development for the High Performance Loop Heat Pipe(LHP) Systems

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Abstract

The Loop Heat Pipe(LHP) system uses capillary forces so as to pump the working fluid from heat acquisition to heat rejecting systems. The performance of the LHP systems depends mainly upon the operating performance of the wick structure. The capillary pressure increases with decreasing the pore size of the wick structure. By the way, the wick structure's permeability decreases with decreasing the pore size and the porosity. To obtain an ideal wick, the wick structure should possess several characteristics such as the small pore size, high porosity and chemical compatibility with working fluid. Sintered metal wicks have been mainly used as the capillary wick structure mounted in LHP because of the fact that the sintered metal wick has some advantages like convenient selection of wick material, smaller pore size and so on as well as high reliability. In this study, sintered metal wicks were developed to meet required several parameters to design the high performance LHP systems for obtaining even more effective cooling technologies.

Nomenclature

A_w : wick cross section area (m^2)
K : permeability (m^2)
k_{eff} : effective conductivity of conductivity (W/mK)
$\dot{m}$: mass rate (kg/s)
P_c : capillary pressure (Pa)
Q : heat rate (W)
r_{eff} : the effective pore radius(m)
T : temperature (℃)
t : thickness (m)
V : volume (m^3)
ϵ : porosity (%)
ρ : density, ($\mathrm{kg/m^3}$)
μ : dynamic viscosity, ($\mathrm{kg/ms}$)
σ : surface tension, ($\mathrm{N/m}$)
l : liquid
v : vapor
$_w$: wick

1. Introduction

The more rapidly the electronic industries has grown, the more significantly the heat generation problem of electronic products has been raised, simultaneously. To improve effectively the cooling

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technology without the environment factors such as noise, size and etc., a heat pipe is generally known well as two-phase heat transfer devices to transport efficiently thermal energy without not only any external power requirements to pump the working fluid but also even at a very small temperature difference.

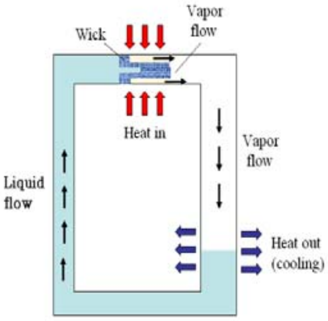
However, even though the heat pipe has several advantages, the heat transport capabilities of the heat pipe are remarkably reduced if a condenser of the heat pipe is located below an evaporator in a gravitational field. Among heat pipes, a Loop Heat Pipe(LHP) system stands recently out due to the fact that the LHP system is unable to be capable of operating effectively at any orientation in a gravitational field over long distances.

The LHP system uses capillary forces in order to pump the working fluid from heat acquisition to heat rejecting systems. As shown in Fig.1, the typical LHP system consists of the condenser, a liquid transport line, a vapor transport line and the evaporator mounted with a wick structure for the capillary pumping. By applying heat load onto the capillary pumping wick structure, the liquid evaporates and the vapor flows to the condenser through the vapor transport line.

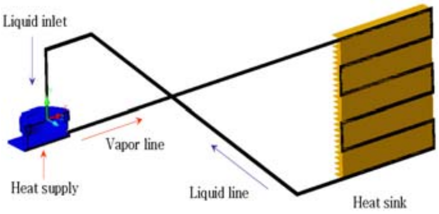
The design of the LHP systems is first required to consider both the evaporator and condenser capability in accordance with applying heat load and operation temperature. The evaporator that consists of a compensation chamber, the wick structure and vapor grooves is actually a section generated in two-phase change of working fluid.

Therefore the wick structure should be decided according to required heat load and operating temperature. That is, the performance of the LHP systems depends mainly upon the operating performance of the wick structure. In addition, the transport lines length and the head are determined according to the LHP system.

Capillary pressure increases with decreasing pore size of the wick structure. But the wick structures' permeability decreases with decreasing the pore size and the porosity. In order to obtain an ideal wick, wick structures should possess several characteristics such as the small pore size, high porosity and chemical compatibility with working fluid.



(a) Operating principle



(b) The schematic diagram

Fig.1 The Loop Heat Pipe(LHP) System

Table.1 The design parameters of the LHP system

No	Parameter	Unit	Required range
1	Heat Load	W	130
2	Operating Temperature	℃	Evaporator : 60 Condenser : 30
3	Pressure Head difference	m	± 0.2
4	Wick thickness	m	0.003 ~ 0.005
5	Effective Thermal conductivity of Wick Structure	W/mK	10 ~ 20
6	Max. Capillary Pressure	kPa	150 ~ 300
7	Porosity	%	50 ~ 60
8	Permeability	m^2	10^{-12} ~ 10^{-14}

Compared with some wick structures such as traditional grooved surface, wire meshes, high density polyethylene and etc., a sintered metal wick has been mainly used as the wick structure because the sintered metal wick has some advantages like convenient selection of wick material and smaller

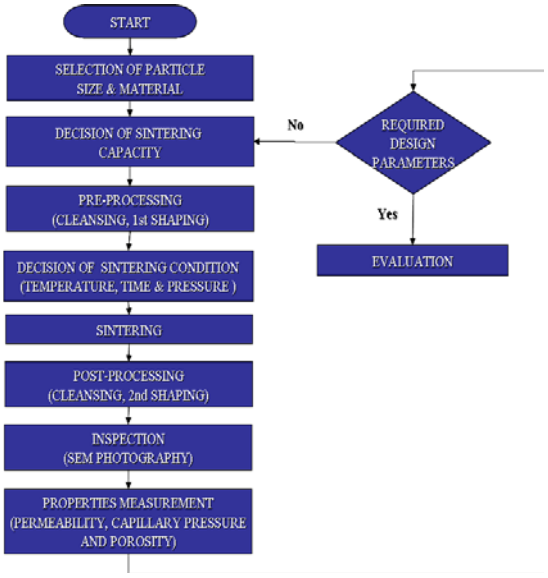


Fig.2 The development processes of the high performance sintered metal wicks

pore size as well as high reliability.

In order to cool effectively high heat load generated on the CPU or/and the other electronic components mounted in either PCs or servers, an excellent cooling technology of the LHP system needs to be definitely designed. In this study, the high performance sintered metal wicks were developed to meet required several parameters as listed in Table.1 to design the LHP system as shown in Fig.1 (b). Then all of the wick structures development processes were conducted as shown in Fig.2.

2. Theories of the wick structure performance parameters

The porosity is defined as the ratio of pore volume V_p and the total volume of the sintered metal wick structure V_t

$$\epsilon = \frac{V_p}{V_t} \qquad (1)$$

and the effective thermal conductivity k_{eff} of the wick structures is defined as

$$k_{eff} = \frac{k_l[(2k_l + k_w) - 2(1-\epsilon)(k_l - k_w)]}{[(2k_l + k_w) + (1-\epsilon)(k_l - k_w)]} \qquad (2)$$

where k_l is the thermal conductivity of working fluid, k_w is the thermal conductivity of wick, and A_w is the wick cross sectional area.

In order to expect analytically the permeability of sintered mental wicks made of sphere powders, Blake-Kozeny presented the experimental equation as under defined,

$$K = \frac{r_s^2 \epsilon^3}{37.5(1-\epsilon)^2} \qquad (3)$$

where r_s is the average sphere radius of powders. Besides, from Young-Laplace equation the maximum capillary pressure can be defined as

$$P_{c,\max} = \frac{2\sigma}{r_{eff}} \qquad (4)$$

where σ is the surface tension coefficient of the working fluid and r_{eff} is the effective pore radius.[4]

3. The fabrication procedure of sintered metal wicks

3.1. Selection among metal powders

For manufacturing sintered wicks, in general, the copper series such as pure copper, bronze and etc. have been selected as the raw materials because they should be compatible with working fluid like distilled water, ethanol and so on. Nevertheless, nickel powders and distilled water were used as raw material and working fluid, respectively in this study. Compared with the existing copper series, nickel is easy to manufacture and has a lower thermal conductivity as well as a lower corrosion. Not only nickel is compatible with the above working fluids as compatible as copper series are, but the manufactured nickel wicks also obtain higher mechanical strength than manufactured copper series. Among various particle sizes, nickel powder provided by ALDRICH (USA) was determined as a particle size in about $3\,\mu\text{m}$ to satisfy required capillary pressure, permeability and porosity as well as smaller pore size subsequent to studying thoroughly each material property.

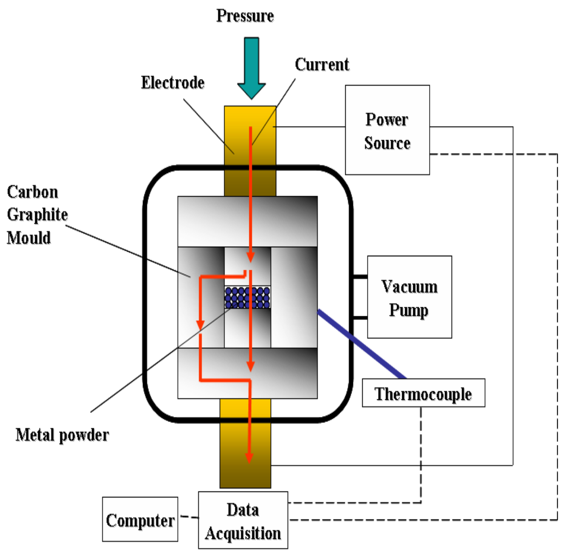


Fig.3 The Schematic of Pulse Electric Current Sintering(PECS) apparatus

3.2. Sintering process

For the manufacturing of the wick structures, among several sintering methods, Pulse Electric Current Sintering(PECS) was adapted in this study. As shown in the Fig. 3, the PECS is performed in carbon graphite moulds using uniaxial pressurization in a vacuum of max. 10^{-3} torr to eliminate the risk of oxidization of nickel powder. Then the temperature of the apparatus was taken by the PID controller and with an accuracy of ±10℃.

In order to meet the required performance parameters as listed in Table.1, the range of the pore radius were asked to be controlled by such sintering parameters as pressure, temperature and time by the sintering processing.

The sintering processing was carried out in accordance with the three-stages program of temperature and time as shown in Fig.4. During the 1st stage, the temperature was ramped by the function dT/dt_r of the rising temperature time t_r. During the 2nd stage, the temperature was kept constant by the hold time t_h. During the 3rd stage, the temperature was finally cooled down by the function dT/dt_c of the cooling temperature time t_c. Then constant pressure was kept all through the sintering time.

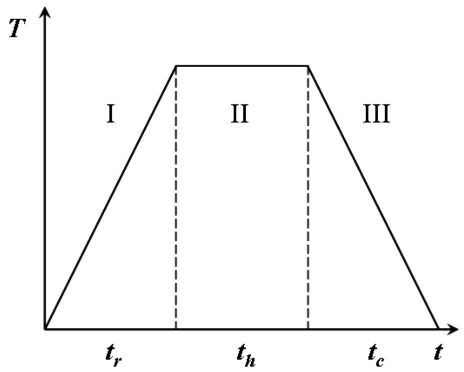


Fig.4 The temperature versus the sintering processing time

4. Sintered wicks' property measurement

4.1 The porosity measurement

A density method was used to measure the porosity. The total density (ρ_p) of porous medium is determined by measuring the outside dimension and weighing the specimen sintered wick on the balance. As the density (ρ_t) of the nickel making up the wick sample of the nonporous state, the porosity of the specimen can be calculated as follows.

$$\epsilon = 1 - \frac{\rho_p}{\rho_t} \qquad (5)$$

4.2 The measurement of Max. capillary pressure and permeability

The permeability is a property of porous media that describe their ability to transport liquid under an applied pressure gradient. To measure the permeability, the mathematical equation of liquid flow in porous media is based on the Darcy's law as defined under.[5]

$$K = \frac{\mu_l \dot{m}_l t_w}{\rho_l A_w \Delta P} \qquad (6)$$

Fig. 5 shows the schematic of an experimental apparatus to measure both the capillary pressure and the permeability. The apparatus consists of a test section, a pressure compensation chamber, a differential pressure gauge. an air tank and a mass

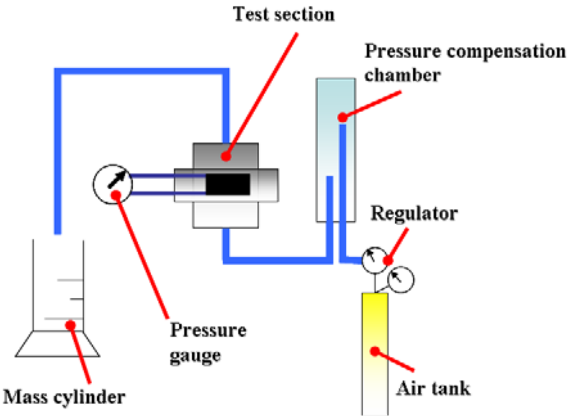


Fig.5 The Schematic of apparatus to measure the capillary pressure along with the permeability

cylinder. The distilled water was transported the pressure compensation chamber to the test section by using constant pressure (0.1 bar) at the air tank taken of the regulator control. And then both the pressure difference and the maximum capillary pressure across a specimen wick set up at the test section were measured by the pressure gauge. At steady conditions, the mass flow rate of distilled water was measured with the help of a stop watch and the mass cylinder.

5. Results

The measuring results were plotted in Fig. 6, which illustrated the relationship between sintering temperature and porosity of the sintered wicks. It was observed that a higher porosity level in the range of 65% to 73% was achieved.

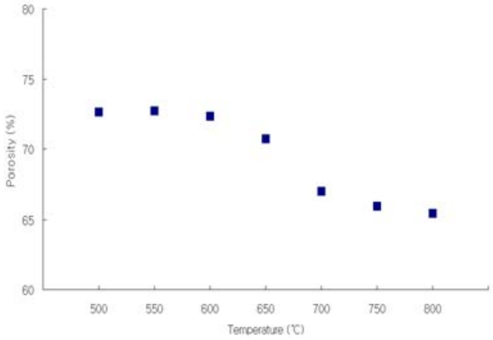


Fig.6 The variation of porosity with each temperature

Apparently, the porosity of the sintered nickel wicks was affected with sintering temperature. Then it was found that the higher porosity of sintered wicks may be acquired by the lowest sintering temperature. However, the case that the lowest sintering temperature, it is difficult to get the high capillary pressure because the pore size increases with decreasing the capillary pressure as mentioned above.

The permeability is the key parameter of the sintered wick to evaluate the flow resistance of working fluid in the wick structure. And then the permeability increases with increasing the pore size and the porosity. However, the capillary pressure increases with decreasing the permeability because of decreasing the pore size.

As shown in Fig.7 and Fig.8 respectively, not only all of the experimental capillary pressure values in ranges of 29.9 to 40.1 kPa but all of the experimental permeability values in range of 10^{-13}

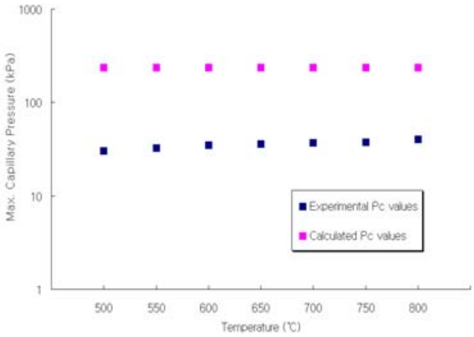


Fig.6 The capillary pressure in accordance with each temperature

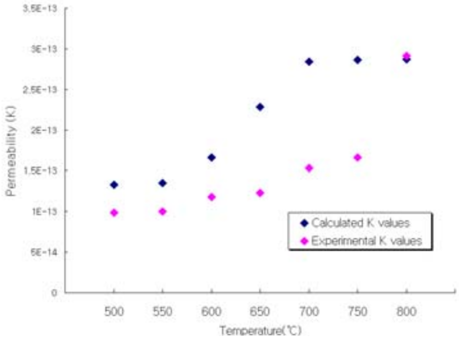
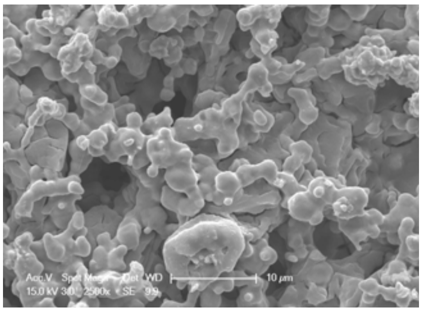
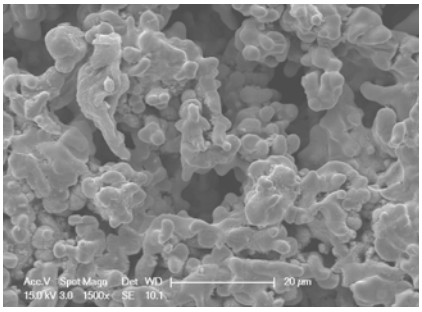


Fig.7 The permeability in accordance with each temperature



(a) The top surface of specimen



(b) The rupture surface of specimen

Fig.8 The SEM photography of the sintered nickel wick

to 10^{-14} m^2 also were obviously satisfied with LHP design parameters which are required as mentioned in Table 1.1 on all of each sintering temperature.

Experimental capillary values were not fully satisfied with calculated capillary pressure values on account of existing pores of different size inside the sintered nickel wick as shown in Fig. 8. Even though the experimental permeability values showed close agreement with the calculated values, there are different between the experimental capillary pressure values and calculated values clearly.

Fig. 8 gives SEM photograph of the microstructure of sintered nickel wicks. The electron micrographs revealed that each pore size of the sintered nickel wicks was ranges of 25μm to 5μm, that is, the uniformly pore size distribution was not observed.

6. Conclusion

The influence of different sintering parameters including sintering temperature, time and pressure as to main properties of sintered metal wick such as the porosity, the mechanical strength and the capillary pressure has been analyzed. As of the sintering processing in this study, over 65% porosity, the pore size ranges of 25μm to 5μm, high mechanical strength, the permeability in range of 10^{-13} to 10^{-14} m^2 and capillary pressure Max. 40kPa can be obtained. As results of this study, the high performance LHP systems can be designed from the development of sintered metal wicks satisfied required performance parameters of the LHP systems in order to cool 130W heat load generated on CPUs and the others mounted in such electronic communication devices, PC and/or severs.

Further experiments have also been conducted for geometry wick structures as well as improving the performance parameters more and more.

Acknowledgement

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