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Effect of Sintering Temperature Curve in Wick Manufactured for Loop Heat Pipe

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***Abstract*—**This investigation examines the effect of the sintering temperature curve in manufactured nickel powder capillary structure (wick) for a loop heat pipe (LHP). The sintering temperature curve is composed of a region of increasing temperature; a region of constant temperature and a region of declining temperature. The most important region is that in which the temperature increases, as an index in the stage in which the temperature increases. The wick of nickel powder is manufactured in the stage of fixed sintering temperature and the time between the stage of constant temperature and the stage of falling temperature. When the slope of the curve in the region of increasing temperature is unity (equivalent to 10 ℃/min), the structure of the wick is complete and the heat transfer performance is optimal. The result of experiment test demonstrates that the heat transfer performance is optimal at 320W; the minimal total thermal resistance is approximately 0.18°C/W, and the heat flux is 17W/cm^2; the internal parameters of the wick are an effective pore radius of 3.1 μm, a permeability of 3.25×10^{-13}m^2 and a porosity of 71%.

***Keywords*—**Loop heat pipe (LHP), capillary structure (wick), sintered temperature curve.

I. INTRODUCTION

DEVELOPED and patented by Maidanik *et al.* [1], the loop heat pipe (LHP) has several engineering applications, including the thermal management of advanced space platforms and military spacecraft, as well as the cooling of electrical and electronic devices. An LHP is composed of an evaporator, with a fine pored capillary structure (wick), and a condenser section that is connected to a separated vapor and liquid flow lines. It exploits latent heat of evaporation and condensation to transfer heat, and depends on the capillary pressure that is generated by the wick structure to circulate the working fluid around the loop.

Based on the principle of inverted menisci, the LHP can achieve a high heat transfer capacity, long transport distance and low thermal resistance, with self-adjustment. Researchers worldwide have investigated various operating characteristics and the design architectures of LHPs [2-8], and have identified the features of these devices as high heat capacity, reliability of operation at adverse tilts in a gravitational field and heat transfer over long distances.

Based on the above literature, an LHP has a high heat transfer capacity, a large transport distance, low thermal resistance, and the capacity to self-adjust. The key determinant of LHP performance is the capacity of the wick. The method by which the wick is manufactured can influence the heat transfer performance of the LHP. Unfortunately, research on manufacturing a wick for use in an LHP is still lacking. Tracey [9] reported that the method of regulating sintering temperature and time can increase the porosity and strengthen the structure of the sintered nickel powder. However, investigations of the regulation of sintering temperature and time are lacking.

Based on the above discussion, the main objective of this investigation is to study the regulation of the sintering temperature curve of the manufactured wick. Wu *et al.* [10] suggested a fixed sintering time of 45 min and a constant temperature of 600 ℃. This investigation also studies the effect of the slope of the sintering temperature curve of a fabricated wick. Finally, a heat transfer performance test is performed in an LHP.

II. EXPERIMENTAL METHOD

A. Wick fabrication

An LHP is composed of an evaporator section, a condenser section, vapor and liquid lines, and a compensation chamber (Fig. 1). The evaporator is equipped with a special wick and joined to a compensation chamber, which receives the working fluid that is displaced from the vapor line and the condenser during the start-up and from the condenser during the operation of the device. By definition of its function, the LHP is a heat-transfer device that operates in a closed evaporation-condensation cycle, using capillary forces to pump a working fluid.

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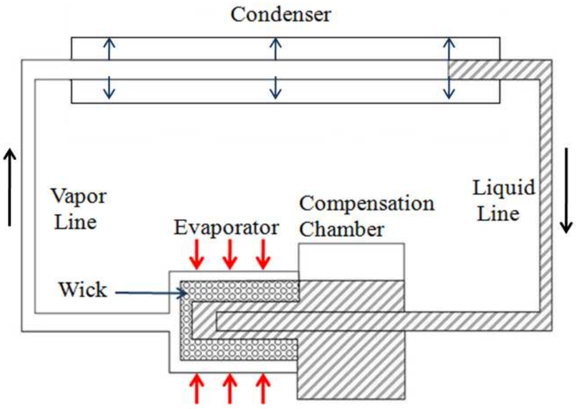

Fig. 1 LHP

To study the effect of regulating the sintering temperature curve of a manufactured wick, various wicks are fabricated from pure Icon type 255 nickel powder with a particle size of 2.2-2.8μm, as in Tracey [11]. The nickel powder is then weighed and a stainless steel mold is filled by hammering. After the sintering temperature curve is regulated, the wick is sintered in (a high-temperature air sintering oven. Following sintering, the mold is stripped off, yielding a wick of nickel powder (Fig. 2).

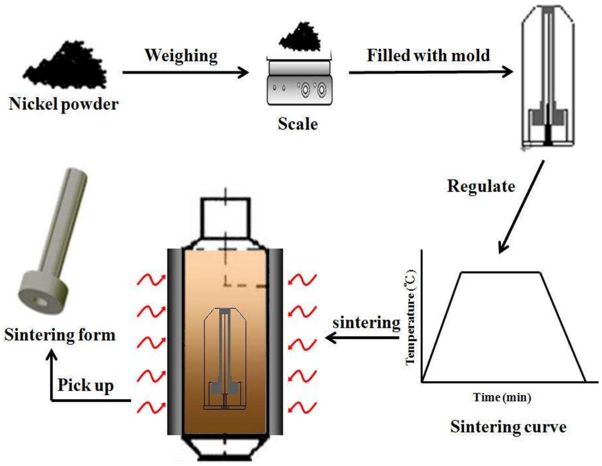

Fig. 2 Wick manufacture

B. *Sintering Temperature Curve*

Regulating the parameters of the manufacturing process of a wick is rather difficult. Hence, in this investigation, the wick parameters are determined form the regulative sintering temperature curve. The sintering temperature curve is determined by sintering temperature and time. Based on the experimental experience of the authors, various sintering temperature curves can be obtained. The sintering temperature curve is composed of (1) a region of increasing temperature, (2) a region of constant temperature, (3) a region of falling temperature. The sintering temperature curve obtained herein is similar to that obtained by Wu *et al.* [10] (Fig. 3). The most important is the region of increasing temperature, which is closely related to the mutual bonding of powder particles.

Based on the effect of the sintering process in various stages of sintering, the sintering temperature curve at fixed temperature and time is anticipated. This investigation is to study the regulation of the sintering temperature curve of the manufactured wick.

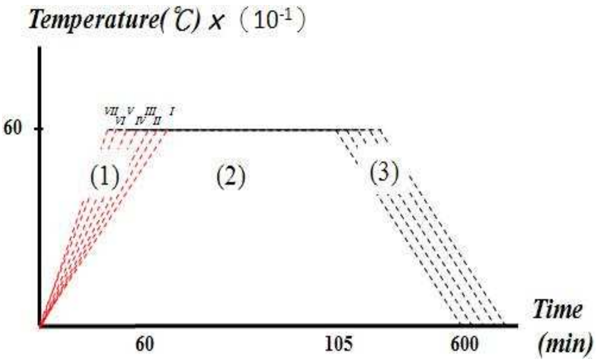

Fig. 3 Typical temperature curve

To show the sensitivity that regulated of increased temperature curve slope which in transition temperature coordinates is constricted 10 times. Therefore, the temperature change is 10℃/min. However, based on the experimental experience of the authors and the range of quality of the wick on which the thermal test can be conducted, the slope of the rising temperature curve is 0.7 (equivalent to 7 ℃/min) to 1.3 (equivalent to 13 ℃/min) (Fig. 3). As the slope of the temperature curve increases, the rate of increase in temperature increases, arrived specified temperature in a short time. When the slope of the temperature curve is 0.7 (equivalent to 7 ℃/min), the wick is too dense to be usable. When the slope of the temperature curve is 1.3 (equivalent to 13 ℃/min), the wick is too loose to be used. This investigation examines the slope of rising temperature curve from type II to VI. Table 1 presents the durations of the increase in temperature for various curve slopes.

TABLE I
DURATION OF INCREASE IN TEMPERATURE

type	slope	time
I	0.7	85
II	0.8	75
III	0.9	65
IV	1	60
V	1.1	55
VI	1.2	50
VII	1.3	45

To study the effect of the slope of the curve of the increase in temperature on the performance in LHP, wicks are manufactured with various slopes to test their heat transfer performance. The external diameter, internal diameter and length of the wick are 12.5mm, 9mm, and 60mm, respectively. Table 1 shows the external dimensions of the proposed LHP system.

TABLE II
LHP SYSTEM PARAMETERS

Evaporator		***Liquid line***	
Length	40 mm	Length	580 mm
Material	Aluminum	***Compensation chamber***	
Vapor line		Length	118 mm
Length	470 mm	***Working fluid***	
Condenser		Ammonia	
		Heat load	50~350(W)
Length	800 mm	***Operating temperature***	10~85 (℃)

C. Evaluation of Internal Parameters of Wick

The internal parameters of a sintered wick are related to its heat transfer performance. The most important internal parameter is determined by evaluating the quality of the sintered wick test pieces. The three main parameters that must be evaluated in the evaluation of a wick are permeability (K_w), maximum effective pore radius (γ), and porosity (ε). These parameters are given by Eqs. (1), (2), and (3). Equations (1), (2), and (3) are not described in detail because of limitations of space. Figure 3 presents the device for measuring the internal parameters of a wick. This device is designed and manufactured according to the aforementioned equations and ASTME128-61 [12].

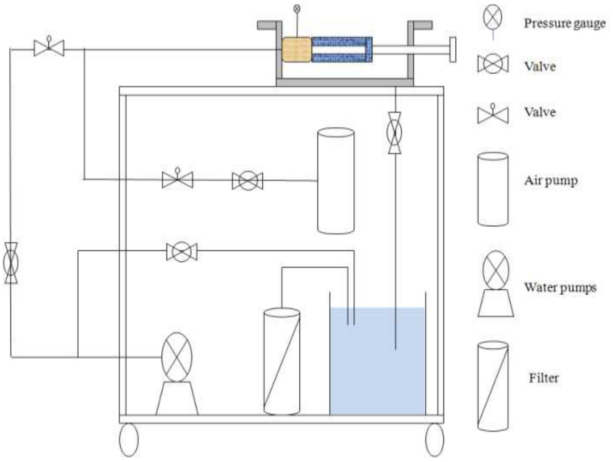

Fig. 4 Device for measuring internal parameters of wick

$$K_w = \mu_l \dot{m} / 2\pi\rho_l \Delta P \, L_w \ln\left(D_o / D_i\right) \tag{1}$$

$$r = 2\sigma / \Delta P \tag{2}$$

$$\varepsilon = \left(W_t - W_w\right) / \left(W_w / M_w\right) \tag{3}$$

D. Test of Heat Transfer Performance of LHP

The performance of all wicks was tested in an almost ambient environment, with the condenser sink temperature maintained at 10 ± 2 ℃ using a water cooler. A heater, connected to a power supply, is adopted to simulate the heat source during the operation of the LHP. The evaporator on the LHP may impose a heat load and generate an initial power of 50W. The evaporator does not stop operating until either the temperature approaches 85℃ or drying occurs. Thermocouple measurements were made and transferred to a computer through a data acquisition device. Additionally, the K-type thermocouple (with a measurement error of ± 0.2℃) is calibrated, and the variation of its measured temperature in the experiment is monitored closely. Based on an analysis of error, Kline and McClintock [13] estimated the overall thermal resistance in Eq. (4) (with an error of ± 5.24%), the permeability in Eq. (1) (with an error of ± 2.62%), the effective pore radius in Eq. (2) (with an error of ± 6.9%) and the porosity in Eq. (3) (with an error of ± 3.9%).

$$R_{total} = \left(T_e - T_c\right) / Q \tag{4}$$

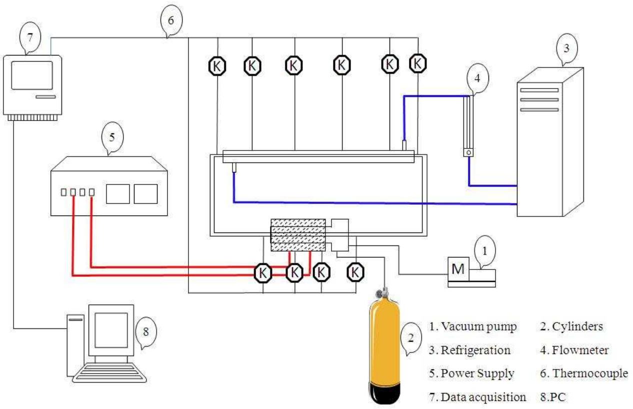

Fig. 5 Device for thermal testing of LHP

III. RESULTS AND DISCUSSION

A. Effect of sintering temperature curve on performance of wick

Table II shows the internal parameters of the wick. A wick that is looser cannot be formed when the slope of the curve of increase in temperature is 1.3 (equivalent to 13℃/min). The ranges tested by Maidanik [6] were an effective pore radius of 0.7 ~ 10 μm, porosity of 60 ~ 75% and permeability of 0.2 ~ 20 × 10^{-13} m^2. The most important internal parameter is permeability.

TABLE III
INTERNAL PARAMETERS OF WICK

Slope	ε (%)	γ (μm)	K_w ($m^2 \times 10^{13}$)
0.7	dense		
0.8	64	0.8	64
0.9	66	0.9	66
1	71	1	71
1.1	69	1.1	69
1.2	61	1.2	61
1.3	loose		

To investigate the effect of the slope of the curve of the increase in temperature on the wick, which internal parameters of the wick are evaluated. The permeability of internal parameters is as an index. In Fig. 6, as the slope of the curve of the increase in temperature increases, the permeability increases. When the slope of the increase in temperature is unity (equivalent to 10℃/min), the wick performance is better. When the slope of the curve of the increase in temperature is less than 0.8 (equivalent to 8 ℃/min), a long sintering time is required, making the wick dense, affecting performance. When the slope of the curve of the increase in temperature exceeds 1.2 (equivalent to 12 ℃/min), the required sintering time is short, making the wick loose, affecting performance. Accordingly, the results obtained using the wick that was manufactured for LHP within revealed three zones of the curve of the increase in temperature. The three zones are (i) a dense zone (with a slope of less than 0.9), (ii) a good zone (with a slope of between 1 to 1.1), and (iii) a loose zone (with a slope of more than 1.2). When the slope of the curve of the increase in temperature is 1.3 (equivalent to 13 ℃/min), the wick is so loose which cannot be formed.

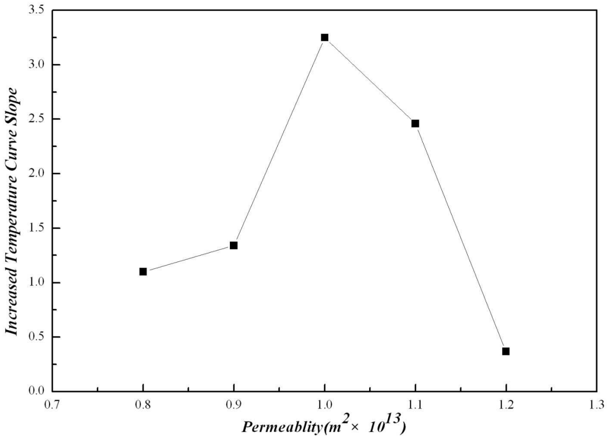

Fig. 6 Relationship between slope of curve of increase in temperature and permeability

B. Analysis of heat transfer performance

All wicks are set into the LHP to test their heat transfer performance, and thereby determine how the slope of the curve of the increase in temperature affects that performance. The heat load is electronically cooled, which process is simulated using a heat sink at 10℃ in an evaporator whose temperature is limited to 85℃ (at a room temperature of 20℃). Thermal testing systems are normally operated a 20 times atmospheric pressure.

Figure 7 plots the relationship between the evaporator temperature (on vertical axis) and the heat load (on horizontal axis). When the heat source is connected to the evaporator, the temperature of the evaporator increases. At a permissible temperature of 85℃, the high heat load corresponds to favorable heat transfer performance. The heat transfer performance of the wick in the LHP varies with the slope of the curve of the increase in temperature. This slope is transformed into an index in the manufacture of the wick. As the slope increases, the rate of increase of temperature increases, but the loosening of the wick detrimentally affects performance, mainly because a higher slope corresponds to a shorter required sintering time, and therefore a weaker mutual bonding among powder particles, finally to an extent so great that the wick cannot even be formed. As the slope decreases, the rate of increase of temperature decreases, and the increasing density of the wick affects performance, primarily because a shorter slope corresponds to the need for a longer sintering time, and therefore a stronger mutual bonding of powder particles, and a denser wick. At a slope of 0.9 (equivalent to 9 ℃/min), the optimal heat load is about 320W (as displayed in Fig. 8).

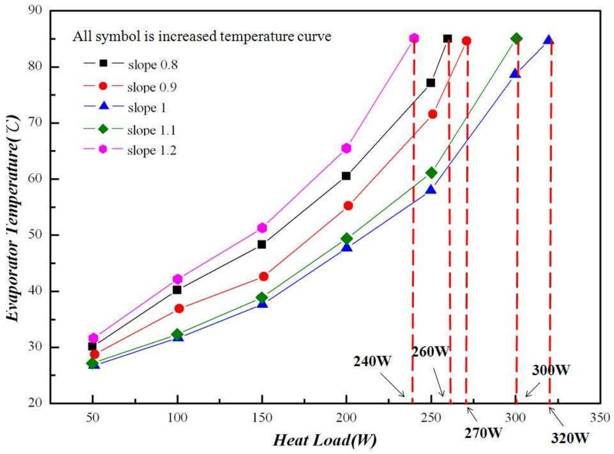

Fig. 7 Relationship between evaporator temperature and heat load

Figure 8 plots the relationship between the total thermal resistance of the system (as a function of the heat load. The wicks are manufactured with curves of the increase of temperature with various slopes, and these are used in LHPs, whose operating mode is consistent the same as that of a traditional LHP. As the heat load increases, the thermal resistance declines. A lower thermal resistance corresponds to a greater heat transfer performance. A heat load of around 150W causes a shift from the zone of variable thermal resistance into the zone of constant thermal resistance. The change in the thermal resistance is responsible for the change in the slope of the curve of the increase in temperature, making the wick looser or denser, affecting the heat transfer performance in the LHP. The results indicate that the heat transfer performance is optimal at a slope of unity (equivalent to 10 ℃/min), and the optimal thermal resistance is approximately 0.18℃/W. The thermal test was carried out at a heat transfer of 320W, a total thermal resistance of 0.18℃/W and a heat flux of 17W/cm^2; the internal parameters of the wick were an effective pore radius of 3.1 μm, a permeability of 3.25×10^{-13}m^2 and a porosity of 71%.

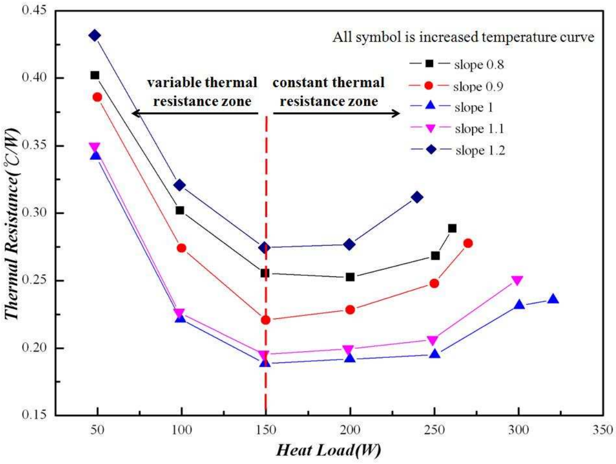

Fig. 8 Relationship between thermal resistance and heat load

C. Sintered temperature curve

From the wick capacity and the results of the thermal test, the optimal slope of the sintering temperature curve is unity (equivalent to 10 ℃/min). The stages of the sintering temperature curve are one of increasing temperature, one of constant temperature and one of falling temperature (Fig. 9). The stage of increasing temperature involves a quantity of 600 ℃ and a duration of 60 min, respectively. The stage of constant temperature involves a sintering temperature of 600℃ and duration of 45 min. The stage of falling temperature involves a sintering temperature of 30℃ and duration of 495 min.

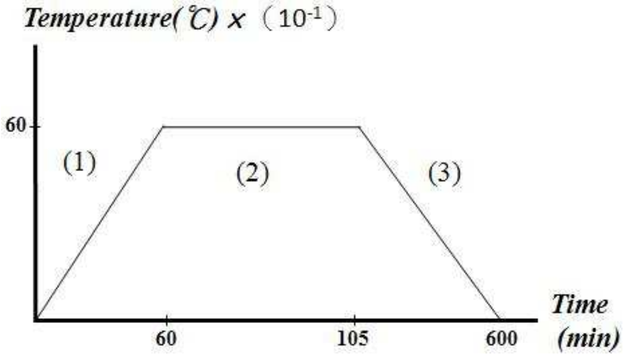

Fig. 9 Sintering Temperature Curve

IV. CONCLUSION

This investigation examined the effect of changes in the slope of the curve of increasing temperature in the manufacture of wicks for LHPs by thermal testing. The following conclusions are drawn.

1. A curve of sintering temperature for nickel powder manufactured wick is obtained. The curve consists of a region of increasing temperature, a region of constant temperature and a region of falling temperature. The densities of the wicks that were manufactured at various points on the curve fell into three zones. The three zones were (i) a dense zone, (ii) a good zone, and (iii) a loose zone.
2. In the stage of the curve of the increase in temperature in which its slope increases, the optimal capability of wick is slope unity (equivalent to 10 ℃/min). From the test results, the internal parameters of the wick are an effective pore radius of 3.1 μm, a permeability of 3.25×10^{-13}m^2 and a porosity of 71%.
3. The results of the thermal test of the wick for LHP indicate that the heat transfer performance is optimal at 320W; the minimum total thermal resistance is about 0.18°C/W, and the heat flux is 17W/cm^2.

NOMENCLATURE

D_o	external diameter of porous material
D_i	internal diameter of porous material
L_w	length of wick
$\dot{m}$	ratio of flow of fluid mass to flow of fluid time
ΔP	capillary force in wick
Q	input “Watt”
R_{total}	total thermal resistance of LHP
T_e	surface temperature of evaporator
T_c	temperature of thermal sink
W_t	weight of wick infused with test fluid
W_w	net weight of wick
σ	surface tension coefficient of fluid
ρ_l	density of fluid
μ_l	viscosity coefficient of fluid

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