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Effective Thermal Conductivity of Moist Porous Sintered Nickel Material[1]

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The effective thermal conductivity of capillary structures is an important parameter in the thermal performance analysis of loop heat pipes (LHP). In this paper, the effective thermal conductivity of porous sintered nickel material filled with water, ethanediol, and glycerin were measured by means of the hot disk thermal constant analyzer. The measured data were compared with similar measured data and calculated values from models in the literature. The results indicate that the thermal conductivity of the porous material depends on the thermal conductivity of the fluid, the filled ratio, and the porosity of the material.

KEY WORDS: effective thermal conductivity; hot disk method; loop heat pipe (LHP), porous sintered nickel.

1. INTRODUCTION

The porous sintered nickel material is usually used in loop heat pipes (LHP) [1, 2]. LHP is becoming increasingly utilized in heat transfer applications, such as space-base satellite applications. Nickel wicks made of porous sintered nickel material are usually used as the capillary structures (CS) of the LHP. The thermal resistance of the LHP strongly depends

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upon the thermophysical properties of the CS. The effective thermal conductivity of the moist porous sintered nickel material used in the CS must be measured, in order to estimate and decrease the thermal resistance of the LHP.

Effective thermal conductivity is a very important parameter of composite materials. There are many different methods to estimate and calculate the effective thermal conductivity of two-phase composite materials. For instance Assad [3] developed a simple model

$$k_e = k_s \left(k_f / k_s\right)^{c\phi} \tag{1}$$

where k_e is the effective thermal conductivity, k_s and k_f are the thermal conductivity of the solid and fluid, respectively, and ϕ is the porosity of the material. $C = 1$ for unconsolidated solids. Chaudary and Bhandari [4] considered the contributions from parallel and series connections of the two phases and suggested

$$k_e = k_{\max}^{n} k_{\min}^{1-n} \tag{2}$$

and
with $0.42 < n < 0.51$, $k_{\max} = \phi k_f + (1 - \phi) k_s$, and $k_{\min} = k_f k_s / (\phi k_s + (1 - \phi) k_f)$. By data correlation Krupiczka [5] obtained a relation,

$$k_e = k_f \left(\frac{k_s}{k_f}\right)^{\left[0.280 - 0.757 \log \phi - 0.057 \log \left(k_s / k_f\right)\right]} \tag{3}$$

Maxwell [6] presented his model as follows:

$$k_e = \frac{k_f \left[2k_f + k_s - 2\phi (k_f - k_s)\right]}{2k_f + k_s + \phi (k_f - k_s)} \tag{4}$$

Russell [7] developed a more complex model,

$$k_e = k_s \left[\frac{\phi^{2/3} + \left(k_s / k_f\right)\left(1 - \phi^{2/3}\right)}{\phi^{2/3} - \phi + \left(k_s / k_f\right)\left(1 - \phi^{2/3} + \phi\right)}\right] \tag{5}$$

Eucken [8] further developed Maxwell's model into

$$k_e = k_s \left[\frac{1 + 2\phi \left(1 - k_s / k_f\right) / \left(2k_s / k_f + 1\right)}{1 - \phi \left(1 - k_s / k_f\right) / \left(2k_s / k_f + 1\right)}\right] \tag{6}$$

Loeb [9] combined the model of Russell [7] and the model of Eucken [8] and proposed that

$$k_e = k_s\,(1 - P_C) + \frac{P_C}{\frac{1}{k_s(1-P_L)} + \frac{P_L k_s}{4G\varepsilon\sigma d T^3}} \tag{7}$$

where P_L is the lengthwise pore ratio, P_C is the crosswise direction pore ratio, G is the geometric coefficient of the pores, σ is the Stefan–Boltzmann constant, ε is the heat emissivity of the radiation surfaces of the pores, T is the average temperature of the material, and d is the longest length of the pores in the heat flux direction. Francl and Kingery [8] pointed out that Eucken's, Russell's, and Loeb's models can only be used when the solid phase is continuous and the porosity is smaller than 50%. Zehner and Schlunder [10] assumed point contacts of particles in the direction of heat flow, and presented a model based on a one-dimensional heat flow model for conduction through a packed bed of spherical particles,

$$k_e = k_f \left\{ 1 - (1-\phi)^{1/2} + \frac{2\,(1-\phi)^{1/2}}{1 - KB} \left[\frac{(1-K)\,B}{(1-KB)^2} \ln\left(\frac{1}{KB}\right) - \frac{B+1}{2} - \frac{B-1}{1-KB} \right] \right\} \tag{8}$$

where $K = k_f/k_s$ and $B = 1.25\,((1-\phi)/\phi)^{10/9}$. Hsu et al. [11], Zeng et al. [12], Pitchumanim [13, 14], and many other researchers have developed methods to estimate the effective thermal conductivity of composite materials.

In this work, the effective thermal conductivity of porous sintered nickel materials with various fluids was measured by means of hot disk thermal constant analyzer; the relations of the effective thermal conductivity and the thermal conductivity of fill fluid and fill ratio were analyzed.

2. MEASUREMENTS

2.1. Specimens

The specimens were preformed and sintered under pressure in cylinders. The materials were carbonyl nickel powders with a mean size of 2 μm, obtained from the Chinese Academy of Space Technology. Two pieces of each specimen were used in the measurements. Specimen 1 is 5 mm thick, has a mass of 11.190 g, a diameter of 26.9 mm, and a porosity of 55.22; Specimen 2 is 4.92 mm thick, had a mass of 10.888 g, a diameter of 26.9 mm, and a porosity of 55.72. Figure 1 is a photo of specimen 1 taken by XT30 ESEM-TMP (Philips). In this photo, the specimen was magnified by 10000.

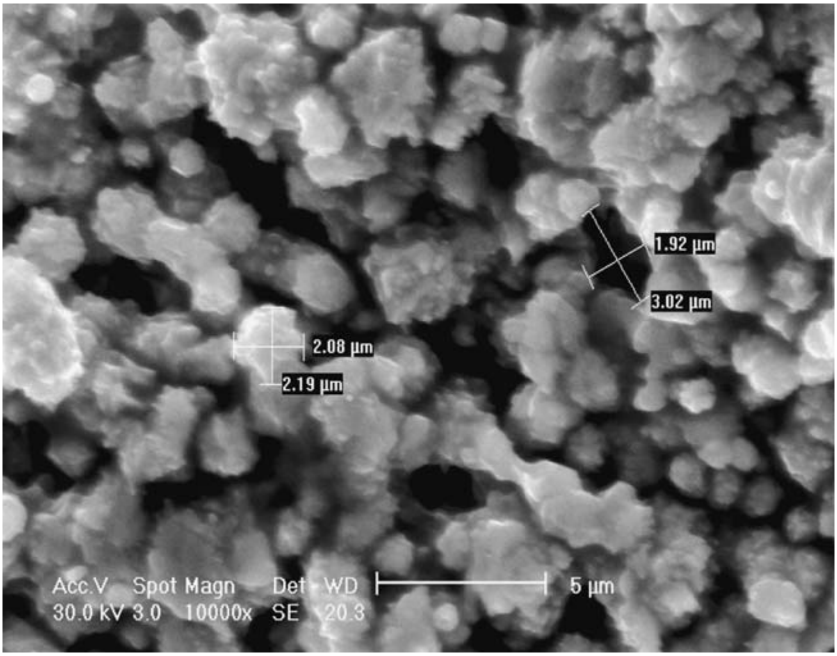

Fig. 1. SEM photo of porous sintered nickel material.

2.2. Experimental Instrument and Procedures

The measuring instrument is the hot disk thermal constants analyzer. The hot disk method is an experimental technique developed from the concept of the transient hot strip (THS) technique, first introduced by Gustafsson et al. [15]. The hot disk analyzer system is based on the transient plane source (TPS) method [16], which is one of the most precise and convenient techniques for studying thermal transport properties. The system components are presented in Fig. 2.

The planar hot disk sensor is placed between two pieces of the specimen and is then heated by an electrical current for a short period of time. The dissipated heat causes a temperature rise of both the sensor and the surrounding specimen. The average temperature rise of the sensor, ranging from 0.5 to 5 K, is measured by recording the change of the electrical resistance. Resistivity changes with temperature and the temperature coefficient of resistivity (TCR) of the sensor material are determined in advance. By comparing the recorded transient temperature rise with that of the theoretical solution of the thermal conductivity equation, the

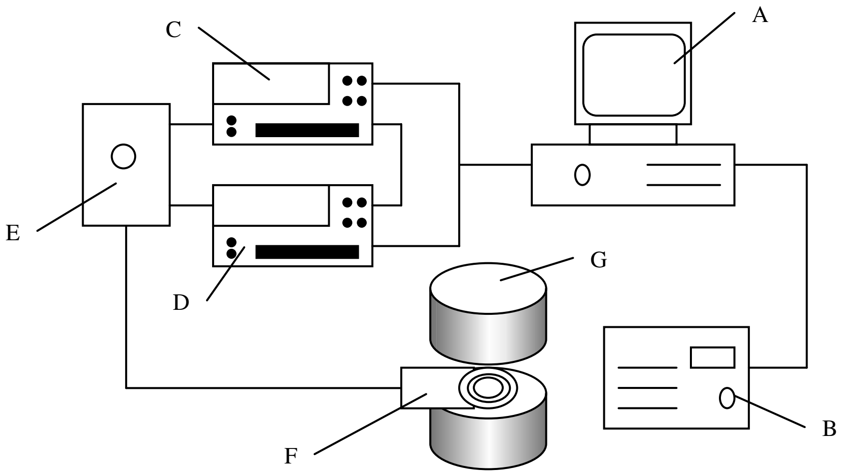

Fig. 2. Hot disk thermal constant analyzer system: (a) computer, (b) computation device, (c) Keithley 2000, (d) Keithley 2400, (e) hot disk bridge, (f) sensor, and (g) samples.

thermal transport properties are deduced, such as the thermal conductivity and the thermal diffusivity, and also the specific heat of the specimen.

Before measurements, the volumes and masses of the specimens were measured and their porosities were calculated. After that, the specimens were filled with a fluid such as water, weighed again, and the filled ratios were calculated. They were sealed in a sample bag for several hours to let the fluid distribute uniformly in the specimens.

3. RESULTS AND DISCUSSION

The effective thermal conductivities of porous sintered nickel, partially saturated with various fluids at 300 K, are listed in Table I and shown in Fig. 3. It is obvious that the effective thermal conductivity of the moist porous material increases as the fill fluid ratio in the pores increases and the thermal conductivity of the fluid increases. When the fill ratio is low, the thermal conductivity increases quickly with increasing moisture saturation; but when the fill ratio increases to a certain value, the increase of the thermal conductivity stabilizes. When the fill ratio is fixed, the effective thermal conductivity increases with the thermal conductivity of the fluid itself.

The effective thermal conductivities of porous sintered nickel with saturated various fluids at different temperatures were measured and listed in Table II. In a limited temperature range, the effective thermal conductivity increases as a smooth curve following the thermal conductivity of the fill fluid.

Table I. Measurement Results of Effective Thermal Conductivity of Porous Sintered Nickel with Partially Saturated Fluid at 300 K

Filled Ratio (%)	Effective Thermal Conductivity[a] ($W \cdot m^{-1} \cdot K^{-1}$)	Standard Deviation[b] ($W \cdot m^{-1} \cdot K^{-1}$)
Filled with Water		
0.0	5.90	0.03
16.4	7.19	0.01
28.2	7.30	0.06
39.6	7.48	0.01
40.0	7.57	0.03
51.0	7.69	0.04
56.4	7.87	0.03
100.0	7.94	0.03
Filled with Ethanediol		
0.0	5.91	0.06
11.6	6.30	0.02
22.9	6.46	0.04
38.3	6.63	0.07
69.8	6.63	0.02
100.0	6.95	0.04
Filled with Glycerin		
0.0	5.90	0.06
17.9	6.83	0.04
40.1	7.06	0.02
58.2	7.21	0.04
100	7.16	0.02

[a]Average value of measured results, each point measured three times.
[b]Standard deviation of the measured results from the average value.

The effective thermal conductivity of porous nickel material obtained by Kiseev and Belonogov [1] is 3.73 $W \cdot m^{-1} \cdot K^{-1}$ when the porosity is 61% and the particle diameter is 0.65 μm and 4.08 $W \cdot m^{-1} \cdot K^{-1}$ when the porosity is 53% and the particle diameter is 0.52 μm. Their results are lower than that obtained in this work. It is because there are some differences between the specimens and measurements. Kiseev and Belonogov used special electrolytic nickel powder to sinter their dendritic structure specimens while we used carbonyl nickel powder to preform and sinter our specimens under pressure. They used a comparative method to measure the effective thermal conductivity while we used the hot disk method. The measured value of the effective thermal conductivity of the porous material depends on the structure and porosity of the specimen, the conditions of sintering, and the measurement method.

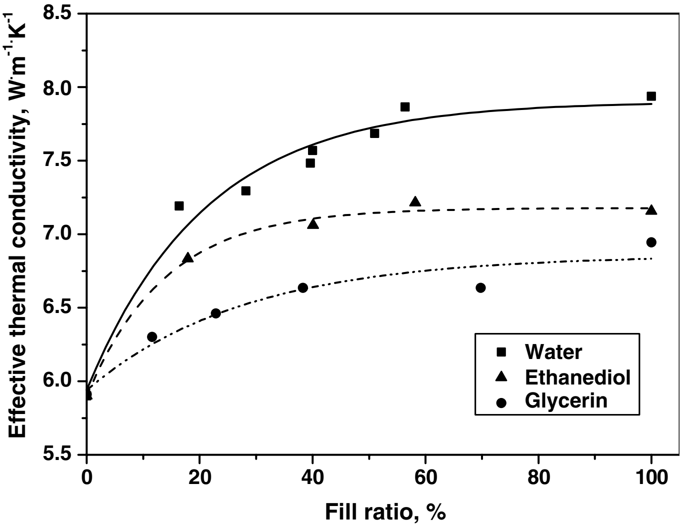

Fig. 3. Effective thermal conductivity of porous sintered nickel with partially saturated fluid.

Table II. Measurement Results of Effective Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$) of Porous Sintered Nickel With Saturated Fluid

	Air	Water			Ethanediol			Glycerin		
Fill Fluid	300 K	300 K	323 K	353 K	300 K	323 K	353 K	300 K	323 K	353 K
k_f [17, 18]	0.026	0.608	0.640	0.669	0.258	0.261	0.265	0.288	0.291	0.295
k_e	5.90	7.94	8.03	8.16	6.95	6.94	7.03	7.16	7.14	7.16

Table III shows the effective thermal conductivities of porous nickel filled with saturated fluids calculated by the models mentioned in the introduction at 300 K. From Table III we can see that the measured data most closely matches with Assad's model [3] and the model of Chaudary and Bhandari [4] using a value of $n = 0.51$. The models of Krupiczka [5] and Maxwell [6] can be used to calculate thermal conductivity of randomly distributed and non-interacting homogeneous solid spheres in a homogeneous continuous medium. The model of Zehner and Schlunder [10] was derived on the assumption that particles are in point contact in the direction of heat flow. In these cases the thermal resistance is large and the calculated results are low for the models of Russell [7] and Eucken [8]. The solid phase is continuous, so the thermal resistance is low and

Table III. Calculated Results for Effective Thermal Conductivity of Porous Sintered Nickel with Saturated Fluid at 300 K[a]

	Effective thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)			
Model	Water	Ethanediol	Glycerin	Air
Assad [3]	9.76	6.57	6.95	2.40
Chaudary and Bhandary [4][b]	8.58	5.56	5.91	1.84
Krupiczka [5]	3.62	1.52	1.73	0.11
Maxwell [6]	2.04	0.85	0.96	0.09
Russell [7]	43.88	43.67	43.69	43.53
Eucken [8]	41.24	41.00	41.02	40.85
Zehnen and Schlunder [10]	5.16	2.62	2.90	0.41
Measured Results	7.94	6.15	7.16	5.90

[a] At 300 K, the thermal conductivity of solid nickel, water, ethanediol, glycerin, and air are 90.5 $W \cdot m^{-1} \cdot K^{-1}$ [17], 0.608 $W \cdot m^{-1} \cdot K^{-1}$ [18], 0.258 $W \cdot m^{-1} \cdot K^{-1}$ [18], 0.288 $W \cdot m^{-1} \cdot K^{-1}$ [18], and 0.026 $W \cdot m^{-1} \cdot K^{-1}$ [18], respectively.
[b] $n = 0.51$.

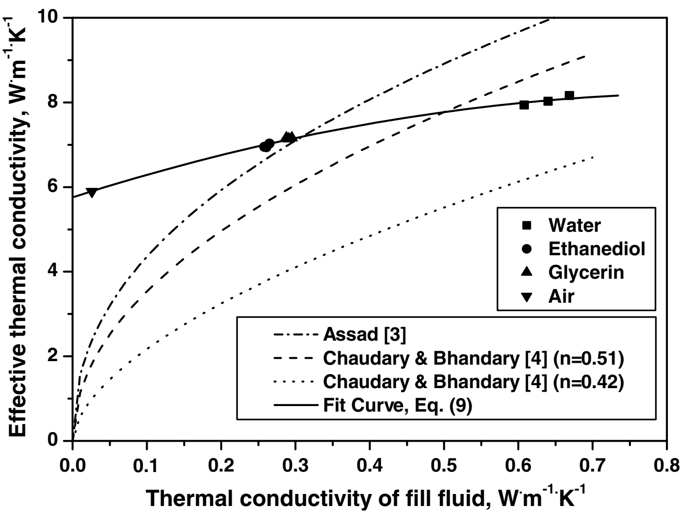

Fig. 4. Effective thermal conductivity of porous sintered nickel with saturated fluid.

the calculated results are large. The experimental values of thermal conductivity are compared to calculated values from the model of Assad [3] and of Chaudary and Bhandary [4] in Fig. 4. It is obvious that the calculated values of the models of Assad and Chaudary and Bhandary drop to zero sharply while the thermal conductivity of the fill fluid approaches zero. Therefore, it is difficult to predict the effective thermal conductivity of porous sintered nickel with saturated fluid using these models. According to the experimental data listed in Table II, a fitted equation is proposed for this porous sintered nickel material with a saturated fluid:

$$k_e = 5.759 + 5.565k_f - 3.094k_f^2 \quad (9)$$

The average absolute deviation and the maximum deviation of Eq. (9) are 0.49 and 0.87%, respectively. In Eq. (9), the suitable range for k_f is from 0 to 0.669 $W \cdot m^{-1} \cdot K^{-1}$, and the temperature range is from 300 to 353 K. Therefore, the effective thermal conductivity of this porous sintered nickel material filled with other kinds of fluids such as ammonia or methanol can be estimated by Eq. (9).

4. CONCLUSIONS

The effective thermal conductivity of the porous sintered nickel specimens were measured with different fill ratio of fluids, such as water, ethanediol, and glycerin, in the pores of the specimens. The effective thermal conductivities of porous sintered nickel with various saturated fluids at different temperature were measured and fitted with a quadratic polynomial equation of the thermal conductivity of the fill fluid. The results can be used to estimate the thermal conductivity of specimens filled with other kinds of fluids.

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