Effects of pore structure characteristics on performance of sintered bi-porous Ti₃AlC₂ wicks

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Abstract

Loop heat pipe, carried out by liquid-gas phase transition, has been attracted as an efficient heat management device in high-heat-flux, long-distance and anti-gravity situations. The capillary pressure provided by the porous wick in the evaporator drives circulation for working liquid, affecting the heat exchange efficiency for loop heat pipes directly. In this work, the bi-porous Ti₃AlC₂ wick was produced by reaction sintering and pore formers dissolution and porosity and pore size were regulated by varying pore formers content and cold pressure. The pore size distribution was characterized by mercury intrusion and effects on capillary performance and thermal conductivity were also analyzed. The porosity and proportion of large pores increased with the increased pore formers content, causing the enhancement of capillary performance and the reduction of thermal conductivity. As the cold pressure increased, pore size distribution concentrated, the proportion of fine pores increased and the porosity fluctuated slightly, increasing the capillary pressure and improving capillary performance and thermal conductivity. Based on experimental results, the parameter of pore size proportion was proposed to modify the Alexander model to predict the thermal conductivity of porous materials accurately, guide the design for pore structure and promote the transfer capacity.

Nomenclature

\( A \) area, \( m^2 \)

\( D_{\text{eff}} \) effective diffusion coefficient, \( m^2 \text{s}^{-1} \)

\( \bar{D} \) equivalent diffusion coefficient, \( m^2\text{s}^{-1} \)

\( d \) diameter, \( m \)

\( H \) capillary height, \( m \)

\( K' \) relative permeability, \( m^2 \text{kg}^{-1} \)

\( L \) length of wick, \( m \)

\( M \) capillary pumping amount, kg

\( P \) proportion of pore size

\( k_{\text{eff}} \) effective thermal conductivity, \( \text{Wm}^{-1}\text{K}^{-1} \)

\( k_f \) fluid thermal conductivity, \( \text{Wm}^{-1}\text{K}^{-1} \)

\( k_s \) solid thermal conductivity, \( \text{Wm}^{-1}\text{K}^{-1} \)

\( t \) time, s

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Greek symbols

\( \varepsilon \) porosity
\( \varepsilon' \) equivalent porosity
\( \rho \) density (kg m\(^{-3}\))
\( \tau \) tortuosity
\( \eta \) kinematic viscosity, m\(^2\) s\(^{-1}\)

Subscripts

\( l \) liquid
\( \text{eff} \) effective
\( i, j \) the certain value of pore size, \( \mu m \)

1. Introduction

As an efficient heat transfer device carried out by liquid-gas phase transition in vacuum, loop heat pipe (LHP) has been widely used for thermal management in industrial fields, such as high-heat-flux semiconductor devices, aircrafts and electronics. This is due to its high thermal management capacity and thermal conductivity, good structure design flexibility, long-distance applicability and excellent anti-gravity capability [1–4].

In general, LHP consists of the evaporator, condenser, vapor line and liquid line. The porous wick in the evaporator provides the capillary pressure and then pumps the working liquid, which is evaporated into liquid to release the heat. It can be seen that the capillary pumping pressure provided by the porous wick in the evaporator plays a significant role in promoting the circulation of the working fluid [5]. Therefore, the high capillary performance is one of the most important characteristics for the desirable wicks in order to achieve excellent heat transfer capacity [6–8].

Recently, a number of approaches have been conducted to prepare porous materials, such as metal powder metallurgy [9–11], fiber processing [12, 13], chemical corrosion [14, 15] and 3D-printing [16, 17]. In addition, pore-forming agents are employed for generating a certain number of pores through subsequent decomposition (such as NH\(_4\)CO\(_3\) [18] and organics [19–21]) or dissolvability (such as NaCl [22–24] and crystalline carbohydrate [25]). Dissolvable NaCl is selected as pore formers in this work, which is an efficient and commercial way to control porosity and pore size by tailoring additions and size of NaCl particles.

Furthermore, thermal conductivity is also crucial for the porous wicks working in the evaporator of LHPs. In general, the capillary wick is expected to have a moderate thermal conductivity. If the thermal conductivity is low, the heat cannot be transferred into the wicks rapidly and homogeneously, resulting in drying the wick partially and decreasing the efficiency of LHPs [26]. However, if the thermal conductivity is too high, heat transportation in the capillary wick could easily induce back heat leak and then accelerate the failure of LHPs [27, 28].

To date, many models have been proposed for the thermal conductivity prediction, as listed in table 1. It is obvious that in the models shown in table 1, gas phase was determined as the mono-sized-spheres dispersed in the porous media randomly and homogeneously. This indicates that the porosity was the only variate for characterizing the pore structure, without considering the pore size effect. In reality, the thermal conductivity of capillary wick is not only determined by the material of capillary wick, but also by the pore structure. The disorder of pore structure, in particular the disorder of pore size distribution, plays a significant influence on heat transfer and heat flow distribution of porous materials [29, 30].

To date, the fractal model and weighting parameters have been applied to reasonably characterize the pore structure [40–42]. Yu et al. [43] proposed a fractal model to calculate the thermal conductivity of non-touchable particles or skeletons and mixed chains with fluid. Giorgio et al. [44] and Licheri et al. [45] applied numerous iterations and the randomization of a Sierpinski carpet and proposed a intermingled fractal units model. The obtained analytical data was in agreement with the experimental values. However, randomization and numerous iterations required high-professional software and arithmetic, restricting the convenience and time efficiency. Carson et al. [46] exploited an empirical weighting parameter to modify the Maxwell’s model in order to express the bounds for ‘internal’ (a sponge or a foam) and ‘external’ (isotropic porous materials) porosity materials. Gong et al. proposed a novel effective thermal theory for a two-phase system with a uniform based medium and successfully acquired the conversion between different models (including Parallel model and EMT model) by modifying the thermal conductivity of the based medium [47]. However, the thermal conductivity of the based medium should remain to be specified, which was not applicable for other porous materials. In this
work, a modified Alexander model based on tortuosity and diffusivity was proposed to predict the thermal conductivity of porous materials, which considered the effect of pore size on pore structure as well.

In this work, Ti3AlC2 was chosen as the porous wick for experimental purpose. As a ternary layered MAX phase, Ti3AlC2 has attracted significant attention. As for the general formula of $M_{\nu+1}AX_n$, $M$ is an early transition metal, $A$ is a IIIA or IVA group element, $X$ is either C or N, and $n$ is 1, 2 or 3 [48]. Due to the combination of both ceramic-like and metal-like properties such as the excellent thermal and electric conductivity [49, 50], low density [51], high strength and fracture toughness [52, 53], easy machinability and good oxidation resistance [54], Ti3AlC2 could be a promising candidate serving as the wicks in the LHP evaporator.

In this work, bi-porous Ti3AlC2 capillary wicks were prepared by reaction sintering and pore formers dissolution. Capillary performance and thermal conductivity were investigated to select the optimal sintering parameters. In order to understand the correlation between pore size proportion and thermal conductivity, a weighting function of porosity based on the tortuosity and diffusivity was proposed to express the pore structure of bi-porous capillary wicks.

2. Materials and methods

2.1. Synthesis of bi-porous wicks

Titanium (~40 μm, 99.9%), Aluminum (~10 μm, 99.9%) and titanium carbide (~10 μm, 99%) powders were weighed in the molar ratio of 2Ti/2Al/3TiC. Off-stoichiometry ratio was chosen to make up for the evaporation loss of Al for obtaining the pure Ti3AlC2. Powders were mixed for 2 h by ball milling and then cold pressed in a graphite die into 20 mm-thick cylinders and then immersed into 85 °C water for 8 h to dissolve pore formers, followed by drying at 110 °C for 2 h.

2.2. Characterization

In this work, the total porosity was determined by the apparent porosity of samples. And the open porosity was measured and calculated according to the Archimedes’ principle shown in equation (1)

$$\varepsilon = \frac{m_1 - m_2 - m_3}{\rho_1 \times V} = \frac{m_1 - m_2 - m_3}{\rho_1 \times L \times \pi R^2}$$

in which $\varepsilon$ is the porosity of samples, $m_1$ is the total beaker mass when the sample is suspended in water for 2 h, $m_2$ is the beaker mass when the saturated sample is removed from water without any water-drop outside, $m_3$ is the mass of dry sample, $\rho_1$ is the density of water, $L$ is the length of the sample, and $R$ is the radius of samples.

The morphology of the wicks was characterized using Backscattered Electron Imaging (BSE, TM4000Plus). Pore size distribution was determined by mercury intrusion porosimetry on an AutoPore IV 9510. Two identical pieces with 4 mm thick were cut from each cylinder bi-porous sample along the axial direction for the thermal

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### Table 1. Models of thermal conductivity of porous material

| Model name                        | Expressions                                                                 |
|-----------------------------------|-----------------------------------------------------------------------------|
| EMT model [31]                    | $k_{\text{eff}} = 0.25\{(3\varepsilon - 1)k_f + [3(1 - \varepsilon) - 1]k_s + \sqrt{(3\varepsilon - 1)k_f + [3(1 - \varepsilon) - 1]k_s}^2 + 8k_fk_s\}$ |
| Alexander model [32]              | $k_{\text{eff}} = k_f \left(\frac{\varepsilon}{\varepsilon + 1}\right)^{\frac{3}{2}} + \varepsilon \cdot k_f$ |
| Zivcova model [33]                | $k_{\text{eff}} = k_s \cdot \left(\frac{1}{\varepsilon + 1}\right)^{\frac{3}{2}}$ |
| Krupicka model [34]               | $k_{\text{eff}} = k_f \left(\frac{\varepsilon}{\varepsilon + 1}\right)^{\frac{3}{2}}$ |
| Chernysheva and Maydanik model [26]| $k_{\text{eff}} = k_f \left(\frac{\varepsilon}{\varepsilon + 1}\right)^{\frac{3}{2}} + \varepsilon \cdot k_f$ |
| Woodside and Messmer model [35]   | $k_{\text{eff}} = \frac{k_f (1 - \varepsilon) + \varepsilon \cdot k_s}{k_f (1 - \varepsilon) + \varepsilon \cdot k_s}$ |
| Maxwell model [36]                | $k_{\text{eff}} = k_f \left(\frac{1 - \varepsilon}{1 - \varepsilon \cdot \varepsilon}\right) + \varepsilon \cdot k_f$ |
| Assad model [37]                  | $k_{\text{eff}} = k_f \left(\frac{1 - \varepsilon}{1 - \varepsilon \cdot \varepsilon}\right)$ |
| Dunn and Reay model [38]          | $k_{\text{eff}} = k_f \left(\frac{1 - \varepsilon}{1 - \varepsilon \cdot \varepsilon}\right) \left(\kappa = \frac{k_f}{k_s}\right)$ |
| Parallel model (Max) [39]         | $k_{\text{eff}} = \varepsilon k_f + (1 - \varepsilon)k_s$ |
conductivity measurement. The measurement was performed with a hot disk thermal constant analyzer (Hot Disk TPS 2500 S) with a probe sandwiched between two identical pieces. Capillary performance was measured through the lab-designed device as shown in figure 1. The end of the capillary wick was in contact with water interface. Due to the capillary force produced by pores, water could be absorbed into the porous sample. The change of the mass loss of water was measured by the electronic balance and recorded by the computer. Then the capillary performance could be described by the curve between the mass loss and time [55, 56].

2.3. Uncertainty analysis
The uncertainty of measurements is based on the accuracy of instruments. For the direct measurements, the accuracy of the electronic balance was 0.1 mg with a measuring range of 0–220 g. The precision of the hot disk thermal constant analyzer (Hot Disk TPS 2500 S) was less than 2%. The uncertainty of the geometry measurement was estimated at about 0.5%–1%. For the indirect measurements, the uncertainty of the porosity depends on the single measurement uncertainty of the mass and volume. The uncertainties of the deduced parameters associated with the single measurement uncertainty were calculated according to the standard error analysis method, and the uncertainties of the porosity was calculated as 1.6%.

3. Results and discussions
3.1. Pore structure characterization
Table 3 lists the respective porosity of the sintering capillary wicks. The porosity of sample 1 was 0.413, which was consistent with the previous results prepared by reaction sintering synthesis [57]. The porosity increased with the increased NaCl content, but changed slightly with the increased cold pressure.

![Figure 1. Schematic diagram of capillary performance characterization.](image)

![Table 2. List of samples with their manufacturing parameters.](table)

| Sample No. | Pore former addition (wt. %) | NaCl powder size (μm) | Cold pressure |
|------------|-------------------------------|----------------------|---------------|
| 1          | 0                             | 38 ~ 48              | 0 MPa         |
| 2          | 10                            | 38 ~ 48              | 0 MPa         |
| 3          | 20                            | 38 ~ 48              | 0 MPa         |
| 4          | 30                            | 38 ~ 48              | 0 MPa         |
| 5          | 30                            | 38 ~ 48              | 10 MPa        |
| 6          | 30                            | 38 ~ 48              | 15 MPa        |
| 7          | 30                            | 38 ~ 48              | 20 MPa        |

The influence of pore formers NaCl and cold pressure on the open porosity and pore size distribution is shown in figure 2, which was derived from the Mercury intrusion porosimetry. As for the sample 1, the pore size demonstrated a normal distribution in the range of 0–2.5 μm, where the pores were generally produced by the gaps between the powders and the synthesis reactions of Ti3AlC2. The employed NaCl maintained the space during the sintering without any reaction with the powders and then left the space as pores after dissolution. As such, large pores (>5 μm) were formed due to the salt dissolution while the fine pores (<2.5 μm) were obtained...
by powder gaps and reaction synthesis. Accordingly, the capillary wicks with a bi-porous structure were prepared.

In figure 2 (a), as the addition of NaCl increased, the distribution curve became broad and the peak size shifted towards large pores gradually, indicating that the open porosity significantly increased (as shown in the inset of figure 2(a)). When the addition of NaCl was over 20%, the curve shapes changed from the ‘single peak’ to the ‘double peaks’. Figure 2(b) showed the pore size distribution as a function of the cold pressure. With the increased cold pressure, the overall porosity just slightly fluctuated (within 0.1) while the open porosity obviously decreased. Meanwhile, these curves were concentrated into a small range gradually and the proportion of fine pores increased. This indicated that it was likely to tailor the open porosity and pore size distribution via varying the cold pressures, but not significantly changing total porosity.

In this work, a parameter of \( P_{i \sim j} \) was defined as the proportion of pores having a specific range of the pore size from the distribution curve, where \( i \) and \( j \) were the values for the pore size between 0 \( \sim 25 \) \( \mu m \). Therefore, \( P_{i \sim j} \) was the ratio of the absolute area having the specific pore size range of \( i \sim j \mu m \) to that of the overall range. Table 3 lists the proportions of fine pores \( (0 \sim 2.5 \mu m) \) and large pores \( (> 5 \mu m) \). With the increasing addition of NaCl, \( P_{0 \sim 2.5} \) decreased sharply while \( P_{>5} \) increased. When the addition of NaCl was 30%, the proportion of large pores occupied 83.61%, suggesting that space-holding of NaCl became dominant in generating pores. With the cold pressure increasing, \( P_{0 \sim 2.5} \) increased slightly while \( P_{>5} \) decreased. As the cold pressure increased, the combination of the closer contact of powders and smaller powder gaps contributed to the increase of fine pores.

Typical morphologies of the prepared bi-porous Ti₃AlC₂ wicks are shown in figure 3 (taking sample 4 as an example). The gray area represented Ti₃AlC₂ while the black area represented pores. During sintering, NaCl particles melted at 800 °C and flowed to connect with the surrounding liquid NaCl particles while Ti/Al/TiC powders reacted with each other. As a consequence, the open porosity increased sensitively with the increased addition of NaCl even though the size of obtained large pores were smaller compared to the NaCl particles size.

### Table 3. Total porosity and pore size proportion of samples.

| Sample No. | Total porosity | \( P_{0 \sim 2.5} (%) \) | \( P_{>5} (%) \) |
|------------|----------------|------------------------|----------------|
| 1          | 0.414          | 95.84                  | 2.99           |
| 2          | 0.531          | 16.64                  | 19.88          |
| 3          | 0.603          | 7.25                   | 76.93          |
| 4          | 0.653          | 5.26                   | 83.61          |
| 5          | 0.638          | 2.60                   | 53.34          |
| 6          | 0.609          | 2.55                   | 44.24          |
| 7          | 0.587          | 1.79                   | 28.08          |

3.2. Capillary performance

As mentioned above, the capillary pressure of the wicks in the evaporator provides the power for cycling the working medium in LHPs, which directly influences the LHP performance and heat transfer efficiency. The capillary suction properties of the wicks under different conditions were measured as shown in figure 4. In figure 4(a), compared to sample 1, NaCl addition obviously promoted the capillary performance with a sharper slope, indicating a higher suction velocity and a shorter time for reaching equivalence. The effect of cold pressure...
on capillary is shown in figure 4(b), where sample 7 showed the best capillary performance and the shortest time for achieving equilibrium, followed by the sample 6. The cold pressure during sintering forced the powders contacting more closely and decreased the pore size, resulting in increasing the proportion of fine pores. This enhanced the capillary pressure, the suction velocity and therefore improved the capillary performance.

According to Darcy’s law, suction curves could be well fitted by the exponential equation described by [12, 55]:

$$M(t) = \rho_l A \varepsilon H(t) = \rho_l A \varepsilon L(1 - e^{-\frac{K'\mu g}{\rho_l}t})$$  \hspace{1cm} (2)

where $M(t)$ and $H(t)$ are the mass and height of capillary pumping respectively, and $K'$ is the relative permeability. Figure 5 shows the relative permeability $K'$ calculated from equation (2). In the evaporator, the permeability of the capillary wick was over $10^{-13}$ m$^2$, which was beneficial for the circulation of the working liquid [10]. In addition, the value of $K'$ increased with the addition of NaCl. Based on the pore structure above, the increasing porosity and $P_{\phi}$ supplied the desirable capillary pressure and sufficient flow channels simultaneously. Accordingly, the flow resistance of working liquid was reduced, which improved the suction velocity and the capillary performance. Even though the porosity of samples was kept similar, $K'$ of samples increased generally with the increasing cold pressure. This was due to the increased proportion of fine pores and the subsequent increased capillary pressure. Considering the porosity, pore size distribution and capillary curves, it could be seen that the capillary performance was predominantly dependent on the porosity, that is, the higher porosity, the better capillary performance. However, under the condition of the similar porosity, the capillary performance was mainly influenced by the pore size distribution and the proportion of fine pores. A concentrated distribution of pore size with the high proportion of fine pores could improve the capillary performance.
3.3. Thermal conductivity of wicks

Porous materials are typically composed of the solid frameworks with a higher thermal conductivity and the working medium (like gas or liquid) with a lower thermal conductivity. Therefore, investigating the thermal conductivity of porous materials has important practical importance. In this work, the solid phase was Ti$_3$AlC$_2$ and the working medium was air. Figure 6(a) shows the experimentally measured thermal conductivity of No. 1 ∼ 4 samples and calculated data from models listed in table 1. It was obvious that Alexander model agreed with the experimental values ($R^2 = 0.96287$), demonstrating its feasibility for predicting the thermal conductivity of porous materials. However, with regard to the samples obtained with different cold pressure (sample No. 4 ∼ 7), as shown in figure 6(b), there was an apparent difference between the experimental values and the calculated data from Alexander model ($R^2 = 0.83817$). This deviation might be due to the fact that the Alexander model only considered the porosity but neglected the effects of proportions of pore size.

In order to predict the thermal conductivity accurately, modifications on the Alexander model was proposed by the consideration of effects of pore size distribution. The equivalent porosity $\varepsilon'$ (expressed by $e' = f(\varepsilon, d, \ldots)$) was proposed and substituted into the Alexander model instead of the porosity $\varepsilon$. Pore size distribution could be determined via the tortuosity of pore channels while the later could be estimated by diffusivity of porous samples as reference. In the porous wicks, effective diffusivity $D_{\text{eff}}$ was written as

$$D_{\text{eff}} = \frac{\varepsilon \bar{D}}{\tau}$$

where $\tau$ was the tortuosity. And the geometric factor of pore channels, given by

$$\tau = \frac{1}{2} \left[ 1 + \frac{1}{2} \sqrt{1 - \varepsilon} + \sqrt{1 - \varepsilon} \left( \frac{1}{\sqrt{1 - \varepsilon}} - 1 \right)^2 + \frac{1}{4} \right]$$

where $\bar{D}$ was the equivalent diffusivity composed of bulk diffusivity $D_b$ and Knudsen diffusivity $D_k$ which was described by the Bosanquet equation

$$\bar{D} = \left( \frac{1}{D_b} + \frac{1}{D_k} \right)^{-1}$$

According to the kinetic theory,

$$D_b = \frac{\lambda v}{3}$$

$$D_k = \frac{d v}{3}$$

where $v$ was the mean molecular velocity, $\lambda$ was the mean free path, and $d$ was the diameter of pores. $K_n$ was Knudsen number, which measured the ratio of molecule-surface and intermolecular collisions and was determined as $K_n = \lambda / d$. Substituting equations (6.1)–(6.2) and Knudsen number into equation (5)
\[ \frac{1}{D} = \frac{1}{D_k} \left( \frac{1 + \frac{1}{K_n}}{n} \right) = \left( 1 + \frac{1}{K_n} \right) \frac{3}{dv} \]  

(7)

Equation (7) could estimate the equivalent diffusivity of single capillary channel. Thus, total equivalent diffusivity of porous media could be given by:

\[ \left( \frac{1}{D} \right)_\text{total} = \sum \left( \frac{1}{D_{i-j}} \times P_{i-j} \right) = \left( 1 + \frac{1}{K_n} \right) \frac{3}{v} \sum \frac{1}{i+j} \times P_{i-j} \]  

(8)

where \( i \) and \( j \) were the pore size of samples with the range of \( 0 \sim 25 \mu m \). For the sake of computation, the first two ranges were set as \( 0 \sim 2.5 \mu m \) and \( 2.5 \sim 5 \mu m \) and the next intervals between levels were chosen as \( 5 \mu m \), for example \( 5 \sim 10 \mu m \) and \( 10 \sim 15 \mu m \).

With the aid of equation (5), effective diffusivity could be expressed as

\[ D_{\text{eff}} = \frac{\varepsilon}{\tau} \frac{K_n}{1 + K_n} \frac{v}{3} \frac{1}{\sum \frac{1}{i+j} \times P_{i-j}} \]  

(9)

As the equivalent porosity was determined by the function of porosity and pore size, \( \varepsilon' = f(\varepsilon, d, \ldots) \). Due to the representation of pore size distribution, the equivalent porosity could be expressed as the function of porosity and effective diffusivity, \( \varepsilon' = g(\varepsilon, D_{\text{eff}}, \ldots) \). According to numerous functions, it was found that the exponential fitting was suitable for the modification. The modified equivalent porosity was given by

\[ \varepsilon' = g(\varepsilon, D_{\text{eff}}, \ldots) = \varepsilon (A + BD_{\text{eff}} C) \]  

(10)

where \( A, B \) and \( C \) were constants, with the value of 1.678, −0.80 and 0.0074 respectively. Table 4 lists the thermal conductivity obtained from experiments and the modified Alexander model. According to statistics, \( R^2 = 0.98104 \) for the samples without cold pressure, while \( R^2 = 0.98776 \) for the samples with various cold pressure, demonstrating the accuracy of the modified model.

As shown in Table 4, the proportion of pore size played an important role in changing the thermal conductivity. The comparative analysis carried out by assuming that there was a fictitious pore structure \( \Psi \) with the porosity as same as sample 1 (i.e. \( \varepsilon_\Psi = \varepsilon_1 = 0.414 \)) and the ‘double-peak’ pore size distribution as same as sample 4

### Table 4. Comparison of thermal conductivity between experimental values and data calculated by modified Alexander model.

| Samples No. | Porosity | \( D_{\text{eff}} \) (m²s⁻¹) | Equivalent porosity \( \varepsilon' \) | \( P_{0.25}(\%) \) | \( P_{>5}(\%) \) | Calculated data \( k_{\text{eff}}' \) with \( \varepsilon' \) (Wm⁻¹K⁻¹) | Experimental values (Wm⁻¹K⁻¹) |
|-------------|----------|-------------------------------|-----------------------------------|----------------|----------------|---------------------------------|-------------------------------|
| 1           | 0.414    | 6.655E-06                     | 0.390                             | 95.84          | 2.99           | 5.53                            | 4.97                          |
| 2           | 0.531    | 1.113E-05                     | 0.499                             | 16.64          | 19.88          | 3.26                            | 2.67                          |
| 3           | 0.603    | 2.437E-05                     | 0.564                             | 7.25           | 76.93          | 2.30                            | 2.36                          |
| 4           | 0.653    | 3.258E-05                     | 0.610                             | 5.26           | 83.61          | 1.79                            | 2.16                          |
| 5           | 0.638    | 1.991E-05                     | 0.597                             | 2.60           | 53.34          | 1.92                            | 2.21                          |
| 6           | 0.609    | 1.841E-05                     | 0.571                             | 2.55           | 44.24          | 2.22                            | 2.32                          |
| 7           | 0.587    | 1.414E-05                     | 0.551                             | 1.79           | 28.08          | 2.50                            | 2.65                          |

**Figure 6.** Comparison of thermal conductivity between models and experimental values (a) samples 1–4, (b) samples 4–7.
of pore size distribution. The thermal conductivity calculated from the modified Alexander model was \( k_{\text{eff}} \psi = 5.64 \text{ W m}^{-1} \text{ K}^{-1} \) which was higher than the data \( k_{\text{eff}} \) as shown in table 4. The deviation indicated the importance of pore size distribution. It could be concluded that the main factor for determining the thermal conductivity of porous materials was porosity and the thermal conductivity decreased with the increased porosity. When the porosity was similar, the thermal conductivity decreased with the increased proportion of fine pores, which was consistent with [47].

4. Conclusions

Bi-porous Ti₃AlC₂ wicks with fine pores (0–2.5 μm) and large pores (>5 μm) were successfully and controllably synthesized by reaction sintering and pore formers dissolution. The regulation of porosity and pore size distribution could be achieved by varying the content of NaCl and the cold pressure.

With the increased NaCl content, the porosity increased and the pore size distribution broadened, changing from the ‘single-peak’ to the ‘double-peaks’. With the increased cold pressure, the porosity fluctuated slightly. Although it was still bi-porous, the pore size distribution curves were concentrated into a small pore size range gradually and the proportion of fine pores increased.

The capillary performance and the thermal conductivity were influenced by the porosity predominantly. With the increased porosity, the capillary performance improved and the thermal conductivity reduced. When the porosity was similar, the capillary performance was determined by the proportion of fine pores. The high proportion of fine pores led to the excellent capillary performance and the low thermal conductivity.

In order to predict the thermal conductivity accurately, the Alexander model was modified by the parameter based on the tortuosity and the diffusivity for the expression of pore size proportion, which would be a comprehensive and accurate approach to predict the thermal conductivity of pore structure and guide the design of pore size distribution.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Declarations of interest

None.

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