

Analysis of Gas Molecule Mean Free Path and Gaseous Thermal Conductivity in Confined Nanoporous Structures

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Received: 31 March 2015 / Accepted: 10 July 2015 / Published online: 24 July 2015
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Abstract This study comprehensively analyzes the mean free path of gas molecules and gaseous thermal conductivity in confined nanoporous structures through a wide range of temperatures and pressures. A simplified unit cell cubic array structure of nanospheres is used to correlate microstructure features with specific surface area and density of nanoporous materials. Zeng’s model is used to describe the mean free path of the gas molecules and the gaseous thermal conductivity in confined nanoporous structures, and experimental gaseous thermal conductivity data from the literature is used to validate the model. The results show that a material’s nanoporous structure features are directly related to specific surface area and density. The mean free path of gas molecules in a confined nanoporous structure decreases with increasing specific surface area and density. Thus, nanoporous materials with a relatively high specific surface area and a higher density are more favorable for confining gaseous thermal conductivity in nanopores. This work shows that $p = 10^4$ Pa and 10^6 Pa are two characteristic pressures at ambient temperatures for the investigated silica aerogel materials. When $p < 10^4$ Pa, the mean free path of the gas molecules remains constant with varying pressure, while gaseous thermal conductivity approaches zero due to the restrictive effect of the nanoporous structure and the diluted gas molecules. When $p > 10^6$ Pa, the limiting effect of the nanoporous structure on the movement of gas molecules can be ignored, and so the mean free path of gas molecules in the nanoporous material approaches the mean free path of gas molecules in free space,

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while the gaseous thermal conductivity approaches the gaseous thermal conductivity in free space. As temperature increases, there exists a maximum value for gaseous thermal conductivity in confined nanoporous materials, but this maximum increases as pressure increases. The maximum gaseous thermal conductivity for the material is also determined in the paper.

Keywords Conduction · Thermophysical properties · Silica aerogel · Nanoporous structure · Mean free path · Thermal conductivity

1 Introduction

Silica aerogel is an amorphous solid material fabricated through sol–gel chemical processing and supercritical drying. The material has many unique physical properties—very high porosity, very high specific surface area, and a low thermal conductivity even lower than that of still air at ambient temperatures—due to its special nanoporous structure [1–6]. Silica aerogel has many different potential applications in super insulation, energy storage, gas absorption, and in improving conventional industrial energy efficiency. Use as a thermal insulation is one of most attractive applications of silica aerogel, and this potential use has been investigated comprehensively in the past two decades. The heat transfer mechanisms in silica aerogel include gaseous conduction, solid conduction, and thermal radiation [7–9]. Convective heat transfer can be ignored completely since the pores in aerogel are nanometer in size [10–13]. However, gaseous thermal conductivity can account for more than 50 % of the total conduction experienced by silica aerogel due to its exceptional porosity, which is typically more than 90 % [4, 5, 13–19]. This gaseous thermal conductivity can potentially be reduced even at atmospheric pressure by reducing pore size for the nanoporous structure. Therefore, in-depth analysis of the gaseous thermal conductivity mechanisms of nanoporous silica aerogels is very important for understanding the insulating performance of the material.

The main reason silica aerogels have a very low thermal conductivity is that the mean pore diameter of aerogel is obviously smaller than the mean free path of gas molecules in free space, which greatly limits the free movement of gas molecules. The heat transfer process is closely related to the collisions between gas molecules as well as the collisions between gas molecules and the surface of the solid. The above collisions directly affect the mean free path of gas molecules in the confined nanoporous structure of silica aerogels. Therefore, correctly estimating and calculating the mean free path is very important for accurately determining the relationship between heat and mass transfer mechanisms in nanoporous structures, and is very significant when estimating gaseous thermal conductivity in nanoporous materials.

Traditionally, the mean free path model in free space is adopted for the gaseous thermal conductivity analysis of conventional porous insulation materials due to the fact that the mean pore diameter in conventional porous materials is micron sized or even larger, which is significantly greater than the mean free path of gas in free space (which is about 70 nm). Generally, the revised gaseous thermal conductivity model (Knudsen equation model) based on the mean free path model in free space is

adopted to determine the effect of pressure on gaseous transportation in conventional porous media [7, 11–20]. It must be mentioned that Knudsen model was derived by analyzing the heat transfer problem between two parallel surfaces. Its validity for gases in porous media is questionable, and especially so for aerogels. The pore dimensions of aerogels are nanometer in scale, and the solid surfaces are a silica matrix distributed over the entire space. Accordingly, the mean free path of gas molecules in confined aerogel nanoporous structures is different because the solid matrix of the aerogel greatly restricts the free movement of gas molecules. By considering nanoporous structure features, Zeng et al. [17] developed a new model in 1995 to depict the mean free path of gas molecules in confined nanostructures. The Zeng model has recently been widely adopted for the analysis of gaseous thermal conductivity in aerogels [14–16, 18–22]. However, it should be noted that, although the mechanisms for gaseous thermal conductivity in aerogels have been studied by many researchers in recent years [18–25], the principles of mean free path variation in nanoporous structures have been largely ignored. Furthermore, the gaseous thermal conductivity analyses performed to date have few been conducted for pressures larger than atmospheric pressure, except the experimental measurement on organic aerogels up to 10 MPa by Swimm et al. [24]. On the other hand, this study comprehensively analyzes the influencing factors, mechanisms, and changes in the mean free path within confined nanoporous structures based on Zeng's model and in combination with a simplified unit cell structure of a cubic array of nanospheres. The gaseous thermal conductivity is also analyzed for wider temperature and pressure ranges than what has previously been reported in the literature.

2 Theoretical Model

2.1 Kinetic Theory of Gases in Free Space

According to the kinetic theory of gases, the inhomogeneous distribution of temperature can lead to a gas molecule exchange, resulting in part of the thermal motion energy transferring from one part of the object to another. The macro-result of this micro-energy transport process is known as the conductive heat transfer of gas. Thus, the magnitude of gaseous thermal conductivity directly depends on the strength of the energy transport process of the gas molecules. This strength primarily comes from three factors: the number of gas molecules involved in energy transport, denoted as the number density; the mean motion velocity of gas molecules u ; and the mean collision frequency between gas molecules f . Accordingly, f/u is the collision frequency per path length of the gas molecules. A larger value of f/u means more frequent collisions between gas molecules, it results to a relatively lower gas molecule mean free path and a relatively longer distance of motion for a single molecule in energy transport routes. Generally, a smaller collision frequency and a larger movement velocity mean a shorter time is required to complete an energy transport process. Furthermore, the gaseous thermal conductivity will increase as the number of molecules involved in the energy transport process increases. The number density of gas molecules is expressed as [17, 26]

$$N_g = p/(k_B T) \quad (1)$$

Here, p is pressure (Pa), T is temperature (K), and $k_B = 1.38 \times 10^{-23} \text{ J}\cdot\text{K}^{-1}$ is the Boltzmann constant.

According to the kinetic theory of gases, the gaseous thermal conductivity is expressed as [17]

$$k = (2.25\gamma - 1.25)0.461N_g M_g u c_v L, \quad (2)$$

where γ is the adiabatic index of gas such that $\gamma = 5/3$ for monatomic gas molecules and $\gamma = 1.4$ for diatomic gas molecules, m_g is the molecular mass, c_v is the specific heat at constant volume, and L is the mean free path of the gas molecules. The mean motion velocity of the gas molecules is calculated as

$$u = \sqrt{8R_m T/(\pi M)} \quad (3)$$

where $R_m = 8.3143 \text{ J}\cdot(\text{mol}\cdot\text{K})^{-1}$ is the universal gas constant and M is the molar mass of the gas molecules. The mean free path of gas molecules in free space is expressed as

$$L_0 = 1/(\sqrt{2}\pi N_g d_g^2), \quad (4)$$

where d_g is the diameter of the gas molecule.

Rearranging the above four equations, the gaseous thermal conductivity in free space is calculated as [17]

$$k_0 = 1.1525(1.8\gamma - 1)k_B c_v \sqrt{MT/(\pi^3 R_m)}/d_g^2. \quad (5)$$

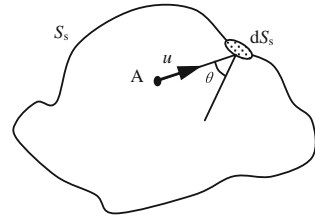
According to Eq. 5, the thermal conductivity for certain gases is independent of pressure and proportional to \sqrt{T} . For air, $\gamma = 1.4$, $c_v = 781.7 \text{ J}\cdot(\text{kg}\cdot\text{K})^{-1}$, $M = 0.029 \text{ kg}\cdot\text{mol}^{-1}$, $d_g = 3.53 \times 10^{-10} \text{ m}$, so the thermal conductivity is

$$k_0 = 1.489 \times 10^{-3} \times \sqrt{T}. \quad (6)$$

2.2 Kinetic Theory of Gases in Confined Nanoporous Structures

In confined nanoporous structures, collisions between gas molecules and the solid surface occur in addition to collisions between gas molecules, and these collisions cannot be ignored. Using the concept of kinetic theory and focusing on the central point A of a gas molecule in a nanoporous structure as shown in Fig. 1, we can determine the volume and the superficial area of the volume (i.e., the area that can collide with point A) where point A cannot exist, and which takes into consideration collisions between the gas molecules as well as collisions between the gas molecules and the solid surface. In this fashion we can obtain the space that point A can occupy. We can also suppose that the possibility the gas molecule occupies any part of the above

Fig. 1 Analysis of collisions of a gas molecule in confined nanoporous structures



space is identical, i.e., the gas molecules move freely and are uniformly distributed in the nanoporous structure. On this basis and applying probability theory, Zeng et al. obtained the collision frequency of the corresponding gas molecule [17]

$$f = \frac{uS_s\rho_{\text{por}}}{4\phi} + \sqrt{2}\pi uN_gd_g^2 \tag{7}$$

Here, S_s is the specific surface area ($\text{m}^2 \cdot \text{g}^{-1}$), ρ_{por} is the density of the porous media ($\text{kg} \cdot \text{m}^{-3}$), and ϕ is the porosity.

The former part of Eq. 7, $f_s = uS_s\rho_{\text{por}}/(4\phi)$, can be considered to be the average collision frequency between gas molecules and the solid surface, while the latter part, $f_g = \sqrt{2}\pi uN_gd_g^2$, would be the average collision frequency between gas molecules. In addition, f_s/f_g is the solid surface collision rate, which characterizes the restriction strength of the nanoporous structure on the gas molecules. Therefore, the mean free path of the gas molecules can be determined directly [17]

$$L_m = u/f = \frac{1}{0.25S_s\rho_{\text{por}}/\phi + \sqrt{2}\pi N_gd_g^2} \tag{8}$$

Zeng et al. then determined the gaseous thermal conductivity in confined nanoporous structures as [4, 17]

$$k_g = \frac{9\gamma - 5}{12} \sqrt{\frac{8M}{\pi R_m}} \frac{c_v p T^{-0.5} \phi}{0.25S_s\rho_{\text{por}}/\phi + \sqrt{2}(p/(k_B T))\pi d_g^2} \tag{9}$$

If air is considered, then

$$k_g = \frac{60.22 \times 10^5 p T^{-0.5} \phi}{0.25S_s\rho_{\text{por}}/\phi + \sqrt{2}(p/(k_B T))\pi d_g^2} \tag{10}$$

2.3 Correlations Between S_s and ϕ and Nanoporous Structures

To use the above equations, the specific surface area S_s and the porosity ϕ of the materials must first be determined in order to calculate the mean free path and the gaseous thermal conductivity in confined nanoporous structures. The porosity of the media can be determined directly by

$$\phi = 1 - \frac{\rho_{\text{por}}}{\rho_{\text{bulk}}} \tag{11}$$

Here, ρ_{bulk} is the density of the bulk material (the value of $\rho_{\text{bulk}} = 2100 \text{ kg} \cdot \text{m}^{-3}$ for bulk silica can be used for silica aerogel [22, 29]). The specific surface area S_s is related to the density and the porous structure features of the material. In order to examine the influencing features of the nanoporous structure, the specific surface area on the mean free path of gas molecules, and the gaseous thermal conductivity in a confined nanoporous structure, this work adopted a regular cubic array structure of nanospheres, as shown in Fig. 2. This cubic array was first recommended by Zeng et al. [27], and adopted by others for their heat transfer analyses [14, 25, 28–30]. In the figure, D is the side length of the column, d is the diameter of the spherical nanoparticles, a is the contact diameter between two nanospheres, and n is the number of nanospheres in each column. Based on Fig. 2(a), the specific surface area S_s and the porosity ϕ can be determined by [28]

$$S_s = \frac{6d}{(d^2 + 0.5a^2) \rho_{\text{bulk}}} \tag{12}$$

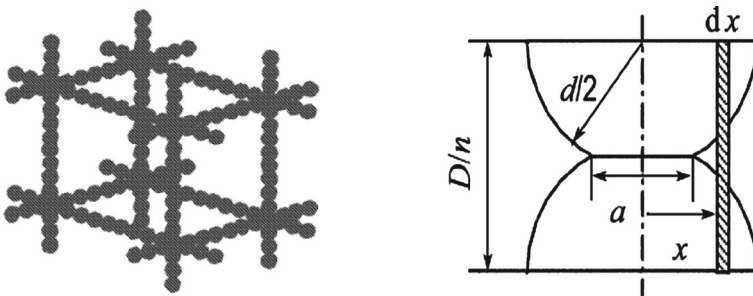
$$\phi = 1 - \frac{\pi (a^2 + 2d^2) (3D - 2\sqrt{d^2 - a^2})}{12D^3} \tag{13}$$

Rearranging the above two equations, we get the following relationships

$$d = \frac{12}{(2 + a_2^2) \rho_{\text{bulk}} S_s} \tag{14}$$

$$D^3 - \frac{3\pi d}{\rho_{\text{por}} S_s} D + \frac{2\pi \sqrt{1 - a_2^2} d^2}{\rho_{\text{por}} S_s} = 0, \tag{15}$$

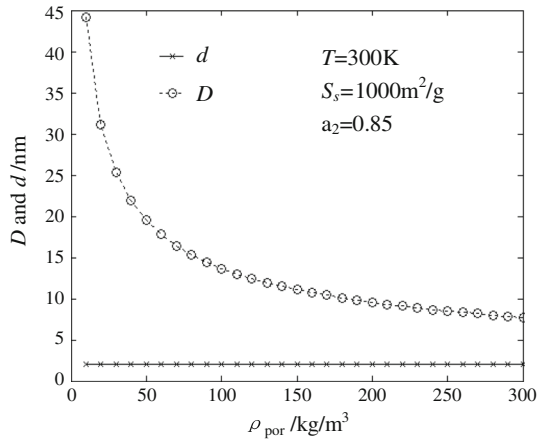
where $a_2 = a/d$. Since density ρ_{por} and specific surface area S_s can be measured through experimental methods (e.g., nitrogen adsorption method), we can then determine the geometric parameters d and D using Eqs. 14 and 15.



(a) Cubic array of nanospherical structures (b) Contact arrangement between two particles

Fig. 2 A simplified geometric structure and the contact arrangement between two nanospherical solid particles [28]

Fig. 3 Effect of density on D and d of a nanoporous aerogel structure



3 Results and Discussion

3.1 Nanoporous Structure Features

Based on Eqs. 14 and 15, the dependent relationship between specific surface area S_s and the nanoporous structure features of the material can be seen in Figs. 3 and 4 (the MATLAB software is used to construct the graphs). The figures show that the particle diameter d changes very little with aerogel density, while the mean pore diameter D is especially evident at lower densities. The specific surface area of the nanoporous material has a profound effect on both particle diameter d and mean pore diameter D , where d and D significantly decrease with increasing specific surface area. Experimental solid grain size for aerogels is in the range of 2 nm to 5 nm, while the mean pore size D is in the range of 10 nm to 50 nm [12,22,27–29], both of which are very close to the calculated results shown in Figs. 3 and 4. Therefore, we can surmise that a cubic array of nanospheres is a reasonable representation of the nanoporous structure of silica aerogel. Based on these nanoporous structure features, we can now discuss the mean free path and gaseous thermal conductivity.

3.2 Validation of the Model and Effect of Pressure

Figure 5 gives the pressure-dependent gaseous thermal conductivity in a confined nanoporous structure. The diameter $d_g = 3.53 \times 10^{-10}$ m was adopted for the air molecules in the calculation. In the figure, the calculated results are also compared against typical experimental data from the literature [14,27]. The validity of this work's theoretical model is verified by these experimental data. Compared with gas molecules in free space (without any confinement), the free movement of gas molecules in a confined nanoporous structure is greatly limited, and the collision probability between gas molecules reduces dramatically. Therefore, the gaseous thermal conductivity in confined nanoporous structures is lower than the gaseous thermal conductivity in free

Fig. 4 Effect of specific surface area on D and d of a nanoporous aerogel structure

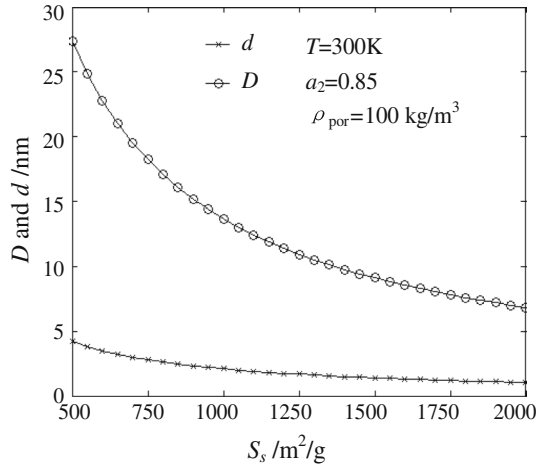
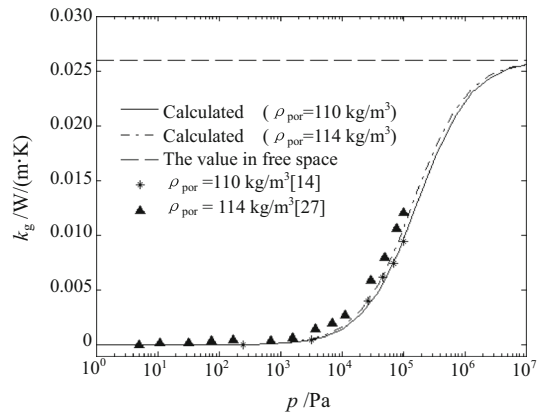


Fig. 5 Effect of gas pressure on gaseous thermal conductivity compared with experimental results

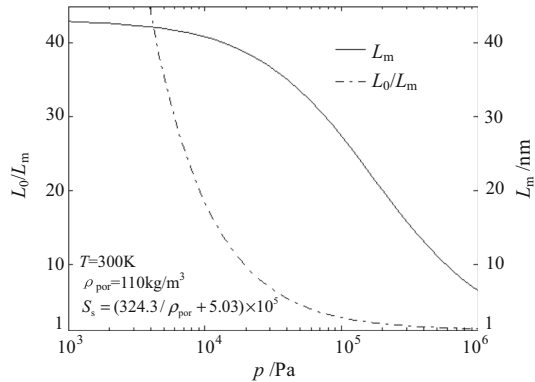


space. When pressure is less than 10^4 Pa, very few gas molecules are involved in energy transport, while the gaseous thermal conductivity approaches zero due to the strong limiting effect of the solid surface. When the pressure is higher than 10^6 Pa, the collisions between gas molecules are bolstered by the increase in the number density of gas molecules, while collisions between gas molecules and the solid surface simultaneously decline. Therefore, the gaseous thermal conductivity in confined nanoporous structures approaches the gaseous thermal conductivity of free space.

The pressure-dependent mean free path of gas molecules in a confined nanoporous structure of aerogel is shown in Fig. 6. Using the mean free path of gas molecules in free space Eqs. 4 and 8, the ratio of L_0/L_m is also plotted in the figure. The ratio L_0/L_m can be considered the nano-scale impact factor for the mean free path of gas molecules, which can clearly characterize the limiting effect of the nanoporous structure on internal gas molecules.

Similar to the variation in gaseous thermal conductivity (Fig. 5), Fig. 6 shows that two characteristic points at about $p = 10^4$ Pa and 10^6 Pa exist for of the variation in

Fig. 6 Effect of gas pressure on mean free path in a confined nanoporous structure



mean free path of gas molecules in a confined nanoporous structure with changing pressure for investigated silica aerogel materials. When $p < 10^4$ Pa, the gas molecule mean free path remains essentially constant with changing pressure due to the restrictive effect of the nanoporous structure, while the number density of the gas molecules is so small that the collisions between gas molecules can be ignored. The gas molecular motion style is usually referred to as the molecular state in this condition. As indicated by Gong [31], the mean free path of gas molecules in the molecular state is approximately proportional to the pore diameter D of aerogel. Since the density and specific surface area of the nanoporous material do not change, the pore diameter D also does not change with variation in pressure. When $p > 10^4$ Pa, the gas molecule mean free path decreases with increasing pressure as the number density of gas molecules also increases. However, the average collision frequency between gas molecules and the solid surface does not change, while the average collision frequency between gas molecules increases. As shown in Fig. 6, the impact factor L_0/L_m decreases with increasing pressure. This means that the restrictive effect of the nanoporous structure on the internal gas molecules weakens with increasing pressure. When $p > 10^6$ Pa, the impact factor L_0/L_m reaches 1 and the limiting effect of the nanoporous structure on the movement of the gas molecules can be ignored. Therefore, the gaseous thermal conductivity approaches the gaseous thermal conductivity in free space.

3.3 Effect of Specific Surface Area and Density

The effect of aerogel specific surface area and density on the mean free path of gas molecules and gaseous thermal conductivity in confined nanoporous structures was analyzed at ambient temperatures and pressures, with the results shown in Figs. 7 and 8. A diameter of $d_g = 3.53 \times 10^{-10}$ m was adopted for the air molecules in the calculations. The results show that the mean free path of gas molecules in a confined nanoporous structure decreases as specific surface area increases, although this trend flattens for very high specific surface areas. At a fixed density, the mean pore diameter D decreases as the specific surface area of a nanoporous structure increases, as shown in Fig. 4. Although the collision frequency between gas molecules does not change, the

Fig. 7 Effect of specific surface area and density on mean free path

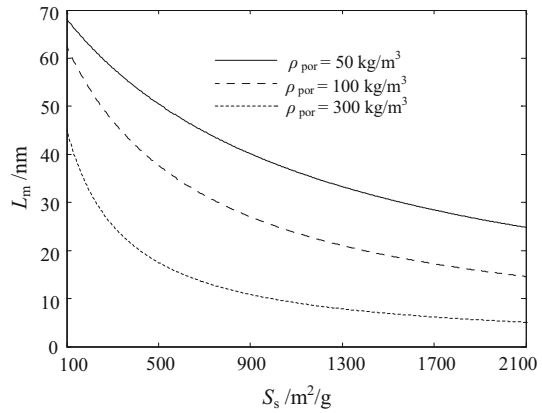
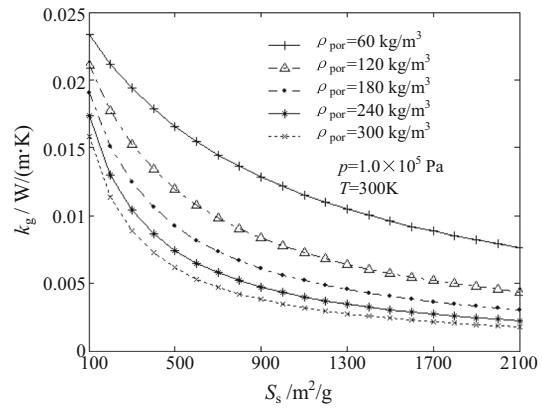


Fig. 8 Effect of specific surface area and density on gaseous thermal conductivity



average collision frequency between gas molecules and the solid walls does increase, reinforcing the restrictive effect of the solid matrix on the motion of the gas molecules. According to Gong et al. [31], the mean free path of gas molecules is approximately proportional to parameter D when the collision frequency between the gas molecules and the wall is large enough to neglect any collisions between gas molecules. Thus, as the rate of change in the mean pore diameter D decreases with increasing specific surface area, so to does the decreasing trend in the mean free path of the gas molecules flatten at high specific surface areas.

For a given specific surface area, the mean pore diameter D decreases with increasing aerogel density, as shown in Fig. 3, while the diameter of solid particle d is unlikely to change. The porosity of the aerogel also decreases with increasing density. Both of these results lead to a reduction in the available space for the free movement of gas molecules in the confined nanoporous structure, which enhances the restrictive effect of the solid matrix on the gas molecules. Therefore, the mean free path of the gas molecules decreases as the density increases (Fig. 7).

Figure 8 shows that the gaseous thermal conductivity in confined nanoporous structures decreases as the density or specific surface area increases. At constant temperature

and pressure, increasing the density of the porous material decreases the mean pore diameter, as shown in Fig. 3, again reinforcing the confining effect of the nanoporous structures on the gas molecules, as mentioned above, and decreasing gaseous thermal conductivity. As the specific surface area increases, the mean pore diameter also decreases, as shown in Fig. 4, because of the reinforced confining effect of the nanoporous structures on the gas molecules, which again decreases gaseous thermal conductivity.

3.4 Effect of Temperature

The variation in mean free path as a function of environmental temperature is shown in Fig. 9. As the temperature rises, the number density of gas molecules decreases because of heat expansion according to Eq. 1. As a result, the scattering cross-section area of gas molecules per unit volume decreases with increasing temperature, which leads to a decrease in the average collision frequency and an increase in the mean free path of the gas molecules. Similarly to the low pressure condition, the gas molecular motion style at high temperatures is also a molecular state, and the gas molecule mean free path is approximately proportional to the mean pore diameter D of the nanoporous material. Therefore, the rate of change of the mean free path of the gas molecules gradually decreases with increasing temperature.

Further investigation of Eq. 9 shows that there is a maximum value for the gaseous thermal conductivity as a result of the change in temperature. Therefore, by deriving k_g as a function of temperature T , the maximum value of gaseous thermal conductivity can be determined when the average collision frequency f_g between gas molecules equals the average collision frequency f_s between gas molecules and the solid surface. This gives the following equation

$$p = \frac{0.25 S_s \rho_{\text{por}} / \phi}{\sqrt{2\pi} d_g^2 / k_B} \cdot T. \quad (16)$$

Substituting Eq. 16 into 9 gives the maximum gaseous thermal conductivity

$$k_g^{\text{max}} = \frac{9\gamma - 5}{12\pi d_g^2} \sqrt{\frac{M}{\pi R_m}} C_v k_B \phi T^{0.5}. \quad (17)$$

Both Eqs. 9 and 17 are plotted in Fig. 10 as a function of temperature and pressure, using a representative value of $S_s = 797 \text{ m}^2 \cdot \text{g}^{-1}$ and a density of $\rho_{\text{por}} = 110 \text{ kg} \cdot \text{m}^{-3}$ [27]. The figure shows that the maximum gaseous thermal conductivity shifts to a higher temperature as the pressure increases.

According to the kinetic theory of gasses, the conductivity of gas molecules in free space is a function of temperature, increasing with elevation of temperature, while the gaseous thermal conductivity in confined nanoporous structures is very different than the one in free space. On the left side of Fig. 10, where the temperature is relatively low and there is a relatively high number density of gas molecules, the molecular collision is the dominant collision type compared to collisions between gas molecules and

Fig. 9 Effect of temperature on mean free path in confined nanoporous structures

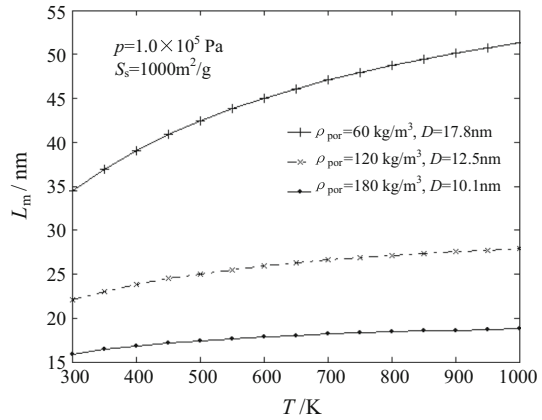
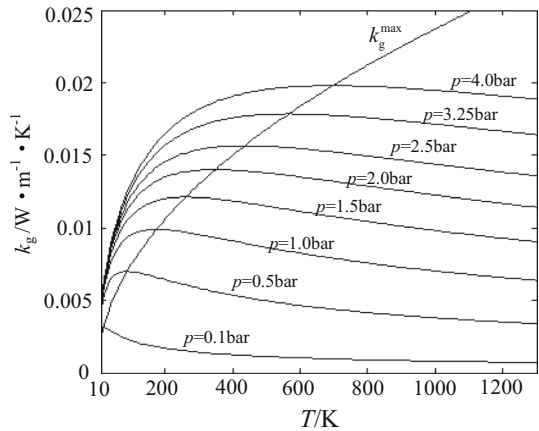


Fig. 10 Effect of temperature on gaseous thermal conductivity in confined nanoporous structures



the solid surface. Therefore, gaseous thermal conductivity increases with increasing temperature, although the rate of increase slows due to the reinforcement of collisions between gas molecules and the solid surface. On the right side of the figure, collisions between gas molecules and the solid surface dominate the molecular collisions, and the number density of gas molecules decreases with increasing temperature, while the heat transfer ability of individual gas molecules does not increase. Therefore, the gaseous thermal conductivity in the confined structure decreases. As the pressure rises, the number density of the gaseous molecules also increases, causing the intermolecular collisions to grow more dominant, so the peak of the gaseous thermal conductivity shifts to the higher temperature side.

4 Conclusions

Gaseous thermal conductivity is one of the main heat transfer mechanisms in nanoporous materials, and is closely related to the collisions between gas molecules

as well as the collisions between gas molecules and the solid surface of the material. The mean free path of gas molecules is a direct representation of these collisions, and so estimating the mean free path is very significant for understanding heat and mass transfer mechanisms in confined nanoporous structures. Although many researchers have studied the gaseous thermal conductivity mechanism in aerogels to some extent, the principles behind changes in mean free path in nanoporous structures have rarely been comprehensively discussed. Using Zeng's model and a simple cubic array unit cell structure of nanospheres, this study analyzed how the mean free path of gas molecules varied in confined nanoporous structures, as well as discussed gaseous thermal conductivity over wide temperature and pressure ranges. The major conclusions are drawn as follows:

1. The structure features of nanoporous materials are directly related to the specific surface area and density. Although the mean pore diameter of aerogel directly affects the mean free path of gas molecules, analyzing the effects of specific surface area and density are more meaningful, i.e., the specific surface area and density are two primary parameters for characterizing nanoporous materials.
2. The mean free path of gas molecules in a confined nanoporous structure decreased with increased specific surface area and with increased density. Nanoporous materials with a relative higher specific surface area and a larger density were more favorable for confining gaseous thermal conductivity in the material's nanopores.
3. $p = 10^4$ Pa and 10^6 Pa are two characteristic pressures at ambient temperature for investigated silica aerogels. When $p < 10^4$ Pa, the mean free path of gas molecules appeared independent of changes in pressure, the gaseous thermal conductivity approached zero due to the restrictive effect of the nanoporous structure, and the number density of the gas molecules was so small that collisions between gas molecules could be ignored. When $p > 10^6$ Pa, the limiting effect of the nanoporous structure on the movement of gas molecules could be ignored, the mean free path of the gas molecules in the nanoporous material approached the mean free path of gas molecules in free space, and the gaseous thermal conductivity approached the conductivity value in free space.
4. With increasing temperature, the mean free path of gas molecules in nanoporous space also increased, although the rate of increase also gradually decreased. A peak gaseous thermal conductivity exists with increased temperature, and this peak value occurred at a higher temperature as the pressure increased. An expression for determining the maximum gaseous thermal conductivity for a nanoporous material has been developed in this study.

Acknowledgments This research was financially supported by the National Natural Science Foundation of China (Nos. 51376060 and 51406052).

References

1. M.S. Douglas, M. Alok, B. Ulrich, J. Non-Cryst. Solids **225**, 254–259 (1998)
2. J. Frick, T. Tillotson, Thin Solid Films **297**, 212–223 (1997)
3. E.R. Bardy, J.C. Mollendorf, D.R. Pendergast, ASME J. Heat Transf. **129**, 232–235 (2007)
4. S.Q. Zeng, A. Hunt, R. Greif, J. Non-Cryst. Solids **186**, 264–270 (1995)

5. K. Raed, U. Gross, *Int. J. Thermophys.* **30**, 1343–1356 (2009)
6. G. Lu, X.D. Wang, Y.Y. Duan, X.W. Li, *J. Non-Cryst. Solids* **357**, 3822–3829 (2011)
7. X. Lu, M.C. Arduinini-Schuster, J. Kuhn, O. Nilsson, J. Fricke, R.W. Pekala, *Science* **225**, 971–972 (1992)
8. S. Spagnol, B. Lartigue, A. Trombe, F. Despetis, *ASME J. Heat Transf.* **131**, 074501–074504 (2009)
9. L.W. Hrubesh, R.W. Pekala, *J. Mater. Res.* **9**, 731–738 (1994)
10. P.J. Burns, C.L. Tien, *Int. J. Heat Mass Transf.* **22**, 929–939 (1979)
11. O.J. Lee, K.H. Lee, J.Y. Tae, J.K. Sun, K.P. Yoo, *J. Non-Cryst. Solids* **298**, 287–292 (2002)
12. X. Lu, R. Caps, J. Fricke, C.T. Alviso, R.W. Pekala, *J. Non-Cryst. Solids* **188**, 226–234 (1995)
13. S.Q. Zeng, A.J. Hunt, W. Cao, *ASME J. Heat Transf.* **116**, 756–759 (1994)
14. G.S. Wei, Y.S. Liu, X.Z. Du, X.X. Zhang, *ASME J. Heat Transf.* **134**, 041301–041306 (2012)
15. G.S. Wei, X.X. Zhang, F. Yu, *J. Univ. Sci. Technol. Beijing* **30**, 781–785 (2008)
16. Y.Y. Duan, J. Lin, X.D. Wang, J.J. Zhao, *CIESC J.* **63**, 54–58 (2012)
17. S.Q. Zeng, A. Hunt, *ASME J. Heat Transf.* **117**, 758–761 (1995)
18. H.J. Wu, Y.D. Liao, Y.F. Ding, H. Wang, C. Peng, *Heat Transf. Eng.* **35**, 1061–1070 (2014)
19. J.J. Zhao, Y.Y. Duan, X.D. Wang, B.X. Wang, *J. Nanopart. Res.* **14**, 1024–1039 (2012)
20. G. Lu, X.D. Wang, Y.Y. Duan, *Aerosp. Mater. Technol.* **1**, 1–6 (2011)
21. G. Lu, Y.Y. Duan, X.D. Wang, *Aerosp. Mater. Technol.* **1**, 29–33 (2011)
22. J.-J. Zhao, PhD Thesis, Tsinghua University, Beijing, 2012
23. G. Reichenauer, U. Heinemann, H.P. Ebert, *Colloids Surf. A* **300**, 204–210 (2007)
24. K. Swimm, G. Reichenauer, S. Vidi, H.P. Ebert, *Int. J. Thermophys.* **30**, 1329–1342 (2009)
25. C. Bi, G.H. Tang, W.Q. Tao, *J. Non-Cryst. Solids* **358**, 3124–3128 (2012)
26. C. Li, L.Y. Zhang, S.W. Qian, *Thermal Science*, 2nd edn. (High Education Press, Beijing, 2008), pp. 91–101
27. S.Q. Zeng, A. Hunt, R. Greif, *ASME J. Heat Transf.* **117**, 1055–1058 (1995)
28. G.S. Wei, X.X. Zhang, F. Yu, *J. Therm. Sci. Technol.* **4**, 107–112 (2005)
29. G.S. Wei, Y.S. Liu, X.X. Zhang, F. Yu, X.Z. Du, *Int. J. Heat Mass Transf.* **54**, 2355–2366 (2011)
30. J.J. Zhao, Y.Y. Duan, X.D. Wang, B.X. Wang, *J. Non-Cryst. Solids* **358**, 1303–1312 (2012)
31. J.H. Gong, *J. Hefei Univ. Technol.* **18**, 143–147 (1995)