# Analysis of coupled heat transfer and thermal conductivity of fiber reinforced silica aerogel composite at high temperatures

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## Introduction

In recent years, fiber reinforced aerogels have received extensive attentions. It is important to characterize the thermal conductivity of aerogels at high temperatures. However, the classic steady-state plate method can only obtain the apparent thermal conductivity of thick sample under large temperature difference. Due to semi-transparent radiation characteristics of fiber reinforced aerogel , the apparent thermal conductivity is affected by the internal skeleton heat conduction, gas molecule heat transfer and radiative heat transfer. Therefore, this paper will investigate the distribution of the apparent thermal conductivity under large temperature differences, and different pressure and high temperature conditions.

## Model Establishment

For thick samples with large temperature differences, the correlation function between apparent thermal conductivity $\bar{\lambda}$ and actual thermal conductivity $\lambda_T$ is expressed as:

$$\bar{\lambda} = \int_{T_L}^{T_H} \lambda_T(T)dT / (T_H - T_L)$$

where:

$T_H$ - hot side temperature, K;

$T_L$ - cold side temperature, K.

Based on Eq. (1), actual thermal conductivity $\lambda_T$ can be determined using the data of apparent thermal conductivities of samples at different hot surface temperatures.

Actual thermal conductivity $\lambda_T$ is relative to the solid-phase thermal conductivity, gas-phase thermal conductivity and radiative thermal conductivity of the aerogel. To decouple the thermal conductivity of each phase, the Rossland diffusion approximation is used to simplify the radiation transfer equation, an approximate formula for radiative thermal conductivity $\lambda_{rad}$ was obtained [1]:

$$\lambda_{rad} = \frac{16}{3\beta_R} n^2 \sigma T^3$$

where:

$\beta_R$ - Rossland extinction coefficient, 1/m;

$n$ - refractive index, -;

$\sigma$ - Stefan–Boltzmann constant, W/m$^2$K$^4$;

$T$ - absolute temperature, K.

For fiber reinforced aerogel with porosity of more than 90%, the gas-phase thermal conductivity can be expressed as using the modified Kaganer model [2]:

$$\lambda_g = \frac{(2.25\gamma - 1.25)0.461(p/k_B T)(8k_B T/\pi m_g)^{1/2}}{0.25 S_s \rho_{por} \varphi^{-1} + \sqrt{2}(p/k_B T)\pi d_g^{\,2}} \frac{c_v}{N_A}$$

where:

$\gamma$ - the ratio of specific heat capacity, -;

$k_B$ - Boltzmann constant, J/K;

$m_g$ - molecular mass, kg;

$S_s$ - surface area per unit mass, m$^2$/kg;

$\rho_{por}$ - apparent density, kg/m$^3$;

$\varphi$ - porosity, -;

$d_g$ - molecular diameter, m;

$c_v$ - molecular diameter, m;

$N_A$ - Avogadro constant, 1/mol.

The coupling of gas-phase thermal conductivity $\lambda_g$ and solid-phase thermal conductivity $\lambda_s$ is defined as gas-solid equivalent thermal conductivity $\lambda_{eff,sg}$. Based on the equivalent model proposed Maxwell-Garnett theory, $\lambda_{eff,sg}$ can be expressed as [3]:

$$\frac{\lambda_{eff,sg} - \lambda_g}{\lambda_{eff,sg} + 2\lambda_g} = \varphi \frac{\lambda_s - \lambda_g}{\lambda_s + 2\lambda_g}$$

Combining Eqs.(1)~(4), the actual thermal conductivity is expressed as :

$$\lambda_T = \lambda_{rad} + \lambda_{eff,sg}$$

## Results and Discussion

The apparent thermal conductivity of fiber reinforced silica aerogel sample under atmospheric pressure are shown in Tab. 1.

**Tab. 1.** Test results of apparent thermal conductivity of fiber reinforced silica aerogel.

| $T_H$ | $T_L$ | $\bar{\lambda}$ |
|---|---|---|
| ℃ | ℃ | ℃ |
| 20.4 | 200 | 0.0283 |
| 21.8 | 400 | 0.0382 |
| 24.2 | 600 | 0.0616 |
| 28.7 | 800 | 0.1044 |
| 32.6 | 900 | 0.1334 |

The spectral radiation properties are shown in Fig.1. The calculated results of thermal conductivities are shown in Fig.2.

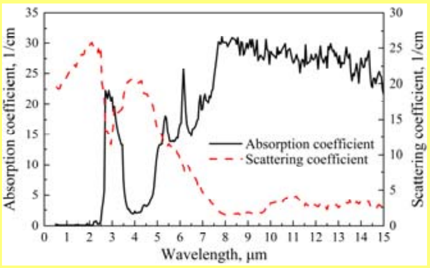


**Fig. 1.** Measurement results of radiation characteristic data of fiber reinforced silica aerogel materials.

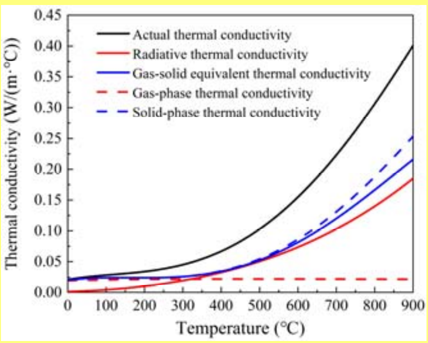


**Fig. 2.** Decoupled results of thermal conductivity of each phase.

The solid-phase thermal conductivity changes greatly with the air pressure, which affects the apparent thermal conductivity. The actual thermal conductivities at different temperatures and pressures are shown in Fig.3. The predicted apparent thermal conductivities of the aerogel sample under different hot surface temperatures and pressures are shown in Fig.4.

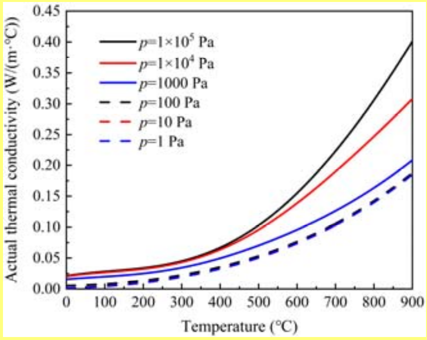


**Fig. 3.** Actual thermal conductivities at different temperatures and pressures.

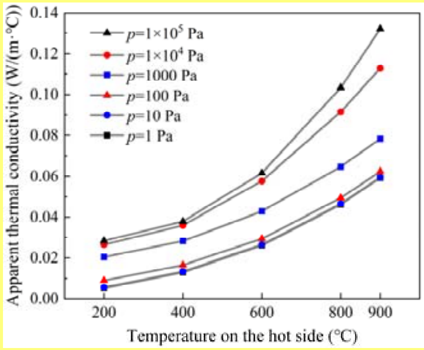


**Fig. 4.** Apparent thermal conductivities at different temperatures and pressures.

## Conclusions

In this paper, the conversion algorithm between apparent thermal conductivity and actual thermal conductivity of fiber reinforced aerogel was established. The Rossland diffusion approximation was used to describe the radiative thermal conductivity, and the modified Kaganer model was used to describe the gas-phase thermal conductivity. Combined with the equivalent model proposed by Maxwell-Garnett theory, the actual thermal conductivity was successfully decoupled. Using the above models, the effects of temperature and pressure on the high-temperature apparent thermal conductivity of aerogel composites were discussed. This paper provides the data for the design and application of fiber reinforced aerogel.

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## References

[1] T. Xie, Y. L. He, Z. J. Hu. Theoretical study on thermal conductivities of silica aerogel composite insulating material. International Journal of Heat and Mass Transfer 58, 540-552 (2013).

[2] S. Q. Zeng, A. Hunt, R. Greif. Mean free path and apparent thermal conductivity of a gas in a porous medium. Journal of Heat Transfer 117, 758-761 (1995).

[3] F. Garoosi. Presenting two new empirical models for calculating the effective dynamic viscosity and thermal conductivity of nanofluids. Powder Technology 366, 788-820 (2020).