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The Model and Experiment for Heat Transfer Characteristics of Nanoporous Silica Aerogel

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Abstract Nanoporous silica aerogel insulation material is both lightweight and efficient; it has important value in the fields of aerospace, petrochemicals, electric metallurgy, shipbuilding, precision instruments, and so on. A theoretical calculation model and experimental measurement of equivalent thermal conductivity for nanoporous silica aerogel insulation material are introduced in this paper. The heat transfer characteristics and thermal insulation principle of aerogel nano are analyzed. The methods of SiO_2 aerogel production are compared. The pressure range of SiO_2 aerogel is 1Pa-atmospheric pressure; the temperature range is room temperature-900K. The pore diameter range of particle SiO_2 aerogel is about 5 to 100 nm, and the average pore diameter range of about 20 ~ 40 nm. These results show that experimental measurements are in good agreement with theoretical calculation values. For nanoporous silica aerogel insulation material, the heat transfer calculation method suitable for nanotechnology can precisely calculate the equivalent thermal conductivity of aerogel nano insulation materials. The network structure is the reason why the thermal conductivity of the aerogel is very low. Heat transfer of materials is mainly realized by convection, radiation, and heat transfer. Therefore, the thermal conductivity of the heat transfer path in aerogel can be reduced by nanotechnology.

Key words aerogel nano, heat transfer characteristics, thermal conductivity.

1. Introduction

Aerogel is a solid substance that is the smallest solid substance in the world. Liang believes that the microstructural effects of aerogel-based vacuum insulation panels under various service times are considered for practical heat transfer engineering, and it is found that the increase in thermal conductivity decreases as the particle size decreases or the pore size increases.[1)] In recent years, proposed heat transfer calculation models for various Aerogel nanoporous materials,[2-12)] but which are not complete and systematic enough. In order to solve the problem of the study on heat transfer characteristics based on nanotechnology is not perfect, and the calculation model of solid phase thermal conductivity coefficient and total thermal conductivity of complex nanotechnology structure is not accurate enough. Through detailed and in-depth research on these problems through the heat transfer calculation method suitable for nanotechnology, the development of equivalent thermal conductivity calculation models of new aerogels nano insulation materials is introduced and analyzed.

2. Proposed Method

2.1 Aerogel Production

As shown in Fig. 1, it is the preparation process of SiO_2 Aerogel. During the Aerogel drying process, the Aerogel is squeezed and shrunk, causing the structure to collapse. Therefore, conventional drying methods cannot be used, and supercritical drying technology is currently widely used. However, supercritical drying needs to be carried out under high temperature and high pressure, and the energy consumption is large, the equipment is complicated, and the price is expensive, which becomes a key factor restricting the large-scale production of Aerogel. The current research hotspot is the atmospheric pressure drying method, and has made certain breakthroughs.

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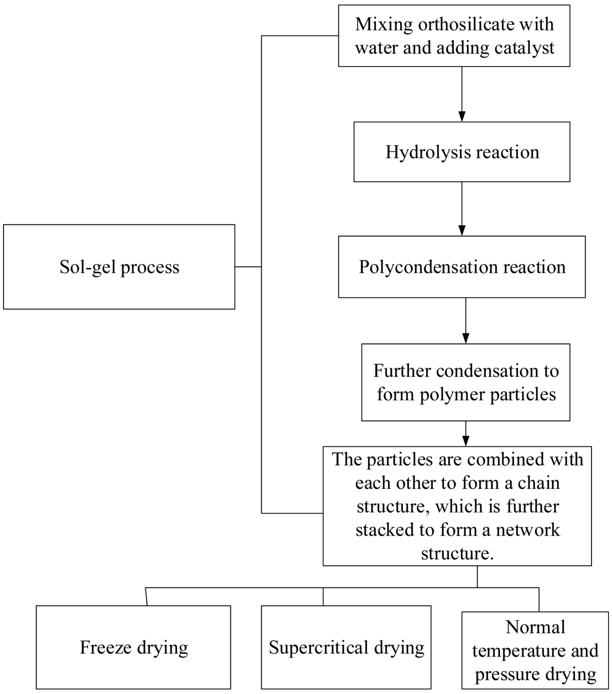

Fig. 1. Preparation process of SiO_2 Aerogel.

2.2 Solid Phase Thermal Conductivity Calculation Method

In order to review the solid-phase heat transfer model materials, this paper is divided into empirical correlation based on experimental data, based on the discussion of dynamic theory derivation model and numerical calculation method based on solving the internal heat transfer equation of solid.

2.2.1 Empirical correlation

For the solid phase thermal conductivity of Aerogel materials. The solid phase thermal conductivity of an Aerogel is in accordance with the power function of the material density:

$$\lambda_s \propto \rho^{1.5} \tag{1}$$

This relationship applies to Aerogel materials with a density of 70 to 300 kg/m^3. It should be noted that, according to experimental data, the above solid phase thermal conductivity is a direct contribution of solid phase heat conduction to the total thermal conductivity.

2.2.2 Theoretical derivation method

The thermal conductivity of the Aerogel solid skeleton can be obtained from the most basic kinetic theory, and the expression of the thermal conductivity of the solid skeleton at the nanometer scale can be obtained. It also reveals the influence of different structural parameters and scale effects on solid-phase heat transfer. Silica Aerogels are a type of semiconductor material that usually depends on the thermal conductivity of the internal phonons.

$$\lambda_s = \frac{1}{3}\rho c_v v_a \Lambda_{ph} = \frac{1}{3}\rho c_v v_a^2 \tau_{ph} \tag{2}$$

Here ρ_{cv} is the volume specific heat of lattice, v_a is the average velocity of phonon, is Λ_{ph} is the average free path of phonon, τ_{ph} is the average relaxation time of phonon, and c_v is the function of temperature.

2.2.3 Numerical simulation method

The numerical simulation methods of thermal conductivity of nano solid materials can be roughly divided into Boltzmann based transport equations and molecular dynamics simulation methods. Similarly, the numerical solution method based on Boltzmann transport equation is first introduced here. Since Boltzmann transport equation is applicable to any aggregate particles satisfying a certain statistical distribution, the law of phonon heat transfer in solids can be obtained.

2.3 Radiation Heat Transfer Calculation Method

Radiation transfer equation: Assume that in the position S emission, absorption and scattering of the participating medium, the direction of the radiant energy transfer, according to the conservation of energy, can derive the governing equation of the radiant energy transfer in the medium, the radiation transfer equation. The expression , emission and scattering media is:

$$\frac{dI_\lambda(s,\mathbf{s})}{ds} = -(\sigma_{a\lambda}+\sigma_{s\lambda})I_\lambda(s,\mathbf{s}) + \sigma_{a\lambda}I_{b\lambda}(s) + \frac{\sigma_{s\lambda}}{4\pi}\int_{4\pi} I_\lambda(s,\mathbf{s}_i)\Phi_\lambda(\mathbf{s}_i,\mathbf{s})d\Omega d\Omega_i \tag{3}$$

Where $I_\lambda(s, \mathbf{s})$ is the spatial position s, the transmission direction $\mathbf{s}$, and the radiation intensity corresponding to the spectrum λ; $\sigma_{a\lambda}$ and $\sigma_{s\lambda}$ are the band absorption and band scattering in the medium, respectively, and the sum of the two is the attenuation coefficient $\sigma_{e\lambda}$, $\Phi_\lambda(\mathbf{s}_i, \mathbf{s})$ is the scatter function. The radiation transfer equation is an integral differential equation, a spatial variable, an angular coordinate variable of two spatial directions, and a total of six independent variables such as one wavelength. At the same time, the radiation transfer equation is also a nonlinear equation, and it is difficult to obtain an exact solution of the equation unless in some simple cases. Therefore, in order to solve this problem, it is necessary to make some hypothesis approximation to the differential integral.

The methods for approximating the solution of the radiation transfer equation can be roughly divided into two categories: one is due to the neglect of the relevant properties of the material itself, another is to make a certain mathematical approximation to the transfer equation.

3. Experiments

3.1. Aerogel Performance Index

As shown in Table 1, the special properties and related applications of Aerogel materials are summarized.

3.2 Nanoscale Heat Transfer Characteristics of Aerogel Insulation Materials

Thermal conduction is a method that relies on the thermal motion of molecules such as molecules, atoms, and free electrons in materials when there is no relative displacement between components within the material. Due to the presence of solid phase components and gas phase components in the Aerogel porous material, heat transfer within the material can be subdivided into solid phase heat transfer and gas phase heat transfer. Gas phase heat conduction is heat transfer caused by collision of gas molecules in the pores. The Aerogel has a pore diameter of 5 to 100 nm and an average pore diameter of about 20 to 40 nm, and the air mean free path in a standard state is about 69 nm.

Similar to the concept of photons in radiation, the minimum energy produced by a solid molecule as a lattice vibration is called a phonon.Taking silica aerogels as an example, the primary particle size is usually 2 to 5 nm. For amorphous silica materials, the mean free path of phonons is about 0.58nm.It can be seen that for Aerogel materials, the skeletal feature scale is also close to the phonon mean free path of the solid, thus causing a significant decrease in solid heat conduction under the effect of the nanoscale effect. Due to the nano-scale solid skeleton particles, the Aerogel solid phase heat transfer is greatly reduced.

4. Discussion

4.1 Analysis of Radiation Heat Transfer Characteristics at Nanoscale

The way in which an object transmits energy by generating electromagnetic waves is called radiant heat transfer. Or scattering. It has a strong permeability of near-infrared radiation having a wavelength of 3 to 8 micrometers at high temperatures, resulting in poor ability of the silicon Aerogel to block infrared radiation at high temperatures. As the temperature increases, the thermal conductivity of the Aerogel increases significantly.

In addition to the three basic heat transfer modes described above, namely gas phase heat conduction, solid phase heat conduction and radiation heat transfer, Aerogel materials are due to the nano-scale pores and solid skeleton of the Aerogel. A large amount of gas molecules are enriched at the contact surface of the solid phase particles, and a large amount of gas molecules are enriched in the slit region. There will be a so-called pseudo-lattice vibration phenomenon that will enhance the overall heat transfer of the material, as shown in Fig. 2.

At the same time, due to various heat transfer modes inside the Aerogel, different heat transfer modes will also affect each other, forming a coupling heat transfer effect. As shown in Fig. 3 (Image from the web: https://wenku.baidu.com/view/12552415d4d8d15abe234ee8.html).

4.2 Comparative Analysis of Aerogel Heat Transfer Characteristics

As shown in Fig. 4, the thermal conductivity of Aerogels is much greater than the thermal conductivity of other materials. The superinsulating properties of Aerogels are based on the principle that due to the existence of an infinite number of nanopores, heat flow can only be transmitted along the walls of the pores as

Table 1. Properties, properties and applications of Aerogel materials.

Nature	Characteristic	Application
Thermal Characteristics	The best solid insulation material; transparent; high temperature resistance; light weight	Building equipment insulation, spacecraft and detection, casting mould
Low Density / High Specific Surface Area / High Porosity	Lightest synthetic solid material; uniform; high specific surface area; multiple components	Catalyst, adsorbent, sensor, fuel storage, ion exchange
Optical Properties	Solid material with low refractive index; transparent; multi-component synthetic material	Light transmissive material; optical coupling material, Cerenkov detector dielectric material
Acoustic Characteristics	Lowest sound velocity material	Range finder, sensor impedance matcher, speaker, building sound absorbing material
Mechanical Properties	Easy to stretch; light weight	Extremely high speed particle trap, energy absorber
Electrical Characteristics	Lowest dielectric constant; high dielectric strength / dielectric strength; high specific surface area	Vacuum electrode spacer, capacitor, integrated circuit dielectric material

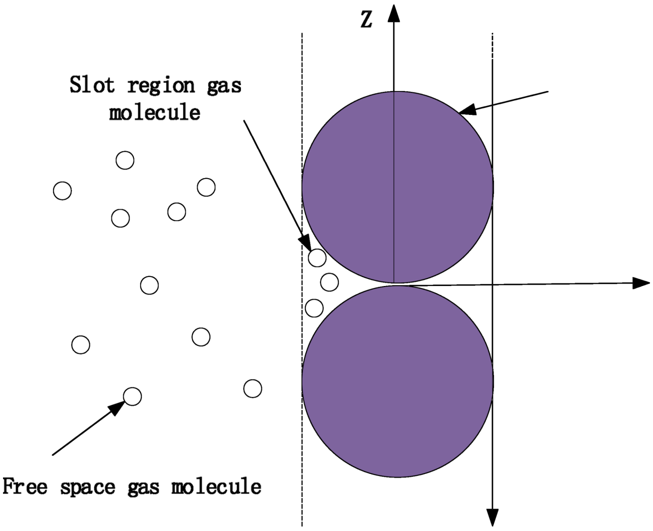

Fig. 2. Gas molecular pseudolattice oscillation in the slit region of aerogel materials.

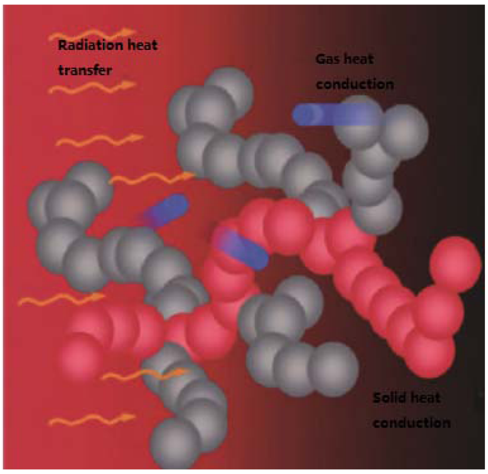

Fig. 3. Gas-solid coupling heat transfer inside Aerogel material.

they propagate through the walls of the pores. The ability to perform solid heat transfer is reduced to near a minimum. When the pore size in the Aerogel material is less than 70 nm, the air molecules in the pores lose their ability to flow freely. Relatively attached to the wall of the hole, the material is in an approximately vacuum state, resulting in a “zero convection” effect. Since the pores in the material are both nano-sized pores and the bulk density of the material itself is very low, the number of pore walls inside the material tends to be “infinite”. For each hole wall, it has the function of a heat shield to reduce radiative heat transfer to near the minimum limit. However, when used at temperatures above 400 °C, it is still necessary to add opacifiers to enhance the resistance of the Aerogel to high temperature infrared radiation.

As shown in Fig. 5 (Image from the web: https://image.baidu.com/search/detail?ct=503316480&z=0&ipn=d&word=%E6%B0%94%E5%87%9D%E8%83%B6%E6%9D%90%E6%96%99%E6%AF%94%E8%BE%83&step_word=&hs=0&pn=277&spn=0&di=145750&pi=0&rn=1&tn=baiduimagedetail&is=0%2C0&istype=2&ie=

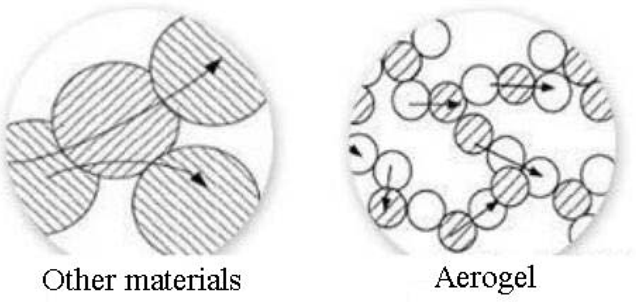

Fig. 5. Schematic diagram of solid heat conduction of Aerogels and other traditional thermal insulation materials.

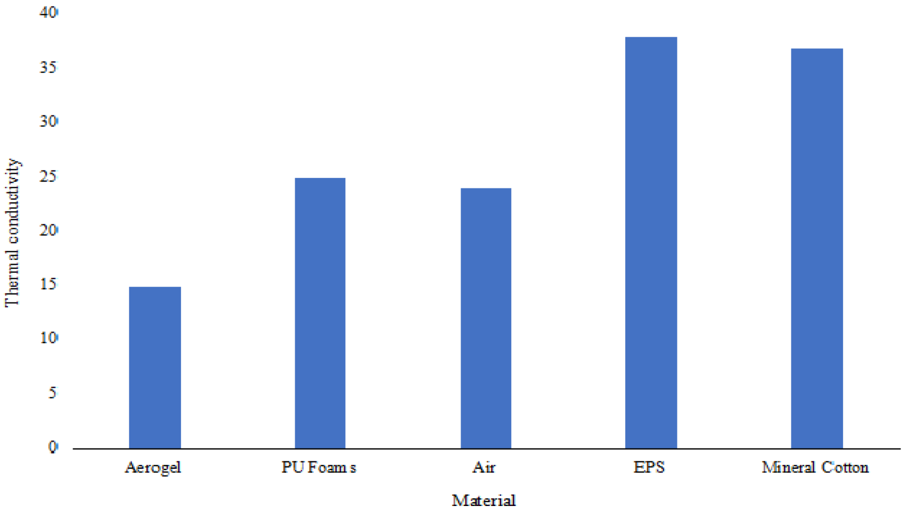

Fig. 4. Comparison of thermal conductivity between Aerogel and traditional thermal insulation materials.

utf-8&oe=utf-8&in=&cl=2&lm=-1&st=-1&cs=1244084734%2C419807296&os=1812441753%2C2351541653&simid=0%2C0&adpicid=0&lpn=0&ln=1098&fr=&fmq=1587641981878_R&fm=result&ic=&s=undefined&hd=&latest=&copyright=&se=&sme=&tab=0&width=&height=&face=undefined&ist=&jit=&cg=&bdtype=0&oriquery=&objurl=http%3A%2F%2F5b0988e595225.cdn.sohucs.com%2Fimages%2F20180711%2Ffcbc517ab6ab4199811d05e9ac682951.jpeg&fromurl=ippr_z2C%24qAzdH3FAzdH3Fooo_z%26e3Bf5i7_z%26e3Bv54AzdH3FwAzdH3Fd9acdlbb8_8aaaadlcc&gsm=116&rpstart=0&rpnum=0&islist=&querylist=&force=undefined), it is a schematic diagram of the solid heat conduction of Aerogels and other conventional thermal insulation materials. Solid heat conduction is heat transfer caused by thermal motion of microscopic particles inside the material. Aerogels have a small framework particle size compared to conventional insulating materials, and the contact area between the particles is also very small, which results in a complicated heat transfer path. In short, if solid heat conduction is a smooth and smooth “highway” in traditional insulating materials, it is a distorted “small intestine” in Aerogels. It can be seen that the solid heat generated in the Kongming Aerogel material is very small.

It is difficult to directly use it as a heat insulating material, and its mechanical properties need to be improved. In view of the above two shortcomings of Aerogel materials, most of the research has focused on enhancing the mechanical properties by adding Aerogel materials with enhancers and sunscreens that reflect, absorb and scatter near-infrared radiation. The addition of these micron-sized functional additives enhances the heat transfer and heat transfer of Aerogel materials due to their high thermal conductivity. On the other hand, because they absorb and scatter radiant heat, it also reduces the radiant heat transfer of the medium inside the material. Therefore, a detailed study of the internal heat transfer mode of Aerogel insulation reveals the heat transfer mechanism, which is of great significance for further reducing the heat transfer performance of nanoporous super-insulating materials. This paper summarizes the existing heat transfer calculation model of Aerogel materials and calculates the heat transfer calculation model of the subsequent Aerogel materials. Its equivalent thermal engineering quick calculations provide some help.

5. Conclusions

(1) The numerical calculation model has used for aerogel nanoporous material stacking structures, and the thermal conductivity of solid particles is calculated.

(2) Compared with traditional thermal insulation materials, the thermal insulation efficiency of the Aerogel in terms of solid heat conduction, gas heat conduction, heat convection, and heat radiation is good, that is, heat transfer efficiency is low. At present, molecular dynamics is rarely used in the heat transfer simulation of Aerogel materials, but its computational properties determine the feasibility of the method to reveal the particle size, contact morphology, gas phase pore size, gas phase atmosphere and other factors.

(3) The basic structure of the Aerogel material is nano-scale pores and a strong skeleton structure. The internal heat transfer mode of Aerogel insulation reveals the heat transfer mechanism, which is of great significance for further reducing the heat transfer performance of nanoporous super-insulating materials.

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