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Effective thermal conductivity of various filling materials for vacuum insulation panels

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ABSTRACT

Three thermal transport mechanisms of various filling materials for Vacuum Insulation Panels (VIPs) are theoretically investigated with special emphasis on the solid conduction. As the first, the solid conductivities of porous materials such as powder, foam, fiber and staggered beam subject to external atmospheric compression are derived using simplified elementary cell models. The results show that the solid conductivities of the fiber and staggered beam insulation are lower than those of the powder and foam due to the relatively long thermal path. The second mechanism, i.e., gaseous conductivity shows the lowest for the fine powder among the considered materials due to its smallest pore size. The radiative conductivity as the last is calculated using the diffusion approximation. If radiation shields are installed for the staggered beam, the radiation effect can be lowered to a negligible order of magnitude. The predicted total effective conductivities suggest that the fiber and staggered beam structures are promisingly proper filling materials for VIPs.

1. Introduction

A recent survey shows that 48% of the total energy consumption in the USA is made in buildings [1]. Needless to say, high performance thermal insulation is increasingly required to reduce energy consumption and/or to save valuable space. A superior thermal insulation can be achieved by so called vacuum insulation panel (VIP). Evacuated insulation enables a VIP to have about 10 times higher thermal resistance than the conventional insulators such as polystyrene or polyurethane foams. Similarly to a conventional Dewar flask or Thermos flask, a VIP makes use of vacuum to suppress the heat transfer due to gaseous conduction. While the Dewar flask has cylindrical shape made of glass or stainless steel wall, the flat type VIP must have a core material which withstands the atmospheric pressure and a gas-tight envelope maintaining the inside vacuum level. The core material has to be porous to easily evacuate and to have minimum conduction heat transfer effect. For this reason, materials in the form of powders, foams and fibers are used as the VIP core material [2]. In addition to the above conventional insulation materials, artificial structures such as staggered beams or honeycomb are proposed for the VIP's filling material [3,4].

Thermal transport in a VIP occurs via solid conduction, gaseous conduction and radiation. The solid conduction depends on the structure and material properties of the core. The gaseous conduction by residual gases depends on the gas pressure which increases with time by infusion of atmospheric gases and outgassing of the inner material. Thermal radiation depends on the structure and optical properties of the core. The total effective conductivity k_{eff} of the VIP can be determined by summation of the solid conductivity k_s, the gaseous conductivity k_g and the radiative conductivity k_r as

$$k_{eff} = k_s + k_g + k_r. \qquad (1)$$

Separate study of each contribution is required to improve the thermal insulation performance of the VIP. However, experimental separate measurement of these contributions is not easy because any of them cannot be fully eliminated. So, a theoretical study on the separate heat transfer mechanisms of the VIP is very instrumental for improving the thermal performance of a VIP.

Numerous studies on the heat transfer mechanisms of the non-evacuated conventional insulators have been conducted. For instance, Chan and Tien [5] analyzed conductance of packed spheres in vacuum. Also, an analytical model for predicting the effective thermal conductivity of packed beds of spheres is developed by Turyk and Yovanovich [6]. Thermal transport mechanisms in closed-cell foam insulations are described by Kuhn et al. [7]. For the fibrous insulation, heat transfer mechanisms are calculated theoretically and compared with the experimental data by Bankvall [8]. However, few studies on the thermal transport mechanisms of the various evacuated insulators are found in the literature.

The aim of this paper is a theoretical investigation of the thermal transport mechanisms with special emphasis on the solid

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Nomenclature

b	width of staggered beam, m	γ	specific heat ratio
e	specific extinction coefficient, m^2/kg	δ	distance between fibers, m
e_λ	spectral specific extinction coefficient, m^2/kg	θ	tilted angle of fibers, radian
E	Young's modulus of elasticity, N/m^2	λ	mean free path, m
E_R	Rossseland mean extinction coefficient, m^{-1}	ν	Poisson's ratio
F	external force, N	Π	porosity
h	height of staggered beam, m	ρ	density, kg/m^3
k	thermal conductivity, W/m K	σ	Stefan-Boltzmann constant
L	length of elementary cell of foam, m	σ_t	tensile strength, N/m^2
M	molecular weight of gas, g/mol	ϕ_τ	pore size, m
n	refractive index		
P	pressure, N/m^2	*Subscripts*	
q	heat flux, W/m^2	*atm*	atmospheric
r	radius, m	*c*	contact
R	thermal resistance, K/W	*eff*	effective
S	conduction shape factor	*f*	fiber
t	thickness, m	*g*	gaseous
T	temperature, K	*m*	mean
W	distance between beams, m	*p*	powder
Z	figure of merit, MPa m K/W	*r*	radiative
		s	solid
Greek symbols		*st*	strut
α	accommodation factor	*th*	thermal

conductivity for various VIP core structures including powder, foam, fiber and the staggered beam core. The solid conductivity is determined via a theoretical model. The gaseous and the radiative conductivities are derived by using separate theoretical models. With the above calculated results, the three heat transfer effects in VIPs are scrutinized in depth.

2. Solid conduction

2.1. Powder insulation

Powders are often used as the filling material in vacuum for cryogenic applications. Materials such as perlite or silica are formed into fine granular particles. It is difficult to completely describe the effective solid conductivity due to the randomness of the packed bed structure. Instead, two cases are investigated using two different models. Firstly, a loose simple cubic arrangement of packed spheres is considered as a typical model (Fig. 1(a)). And then, a hexagonal close-packed model is analyzed (Fig. 1(b)).

The contact resistance can be calculated using Hertz contact theory [9]. The contact modulus defining the elastic properties of spheres 1 and 2 is given by

$$\frac{1}{E_0} = \frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}, \tag{2}$$

where E is Young's modulus and ν is Poisson's ratio. A radius r_0 named as the relative contact radius is expressed by summation of each curvature;

$$\frac{1}{r_0} = \frac{1}{r_1} + \frac{1}{r_2}. \tag{3}$$

The true radius of contact circle r_c is then

$$r_c = \left(\frac{3Fr_0}{4E_0}\right)^{1/3}, \tag{4}$$

where F is the external force loaded on the sphere.

Consider the simple cubic model of Fig. 1(a). Since it can be assumed that the contact radius is very small compared to the size of the sphere, the conduction may be treated using the conduction shape factor [10] involving a disk of radius r_c placed on semi-infi-

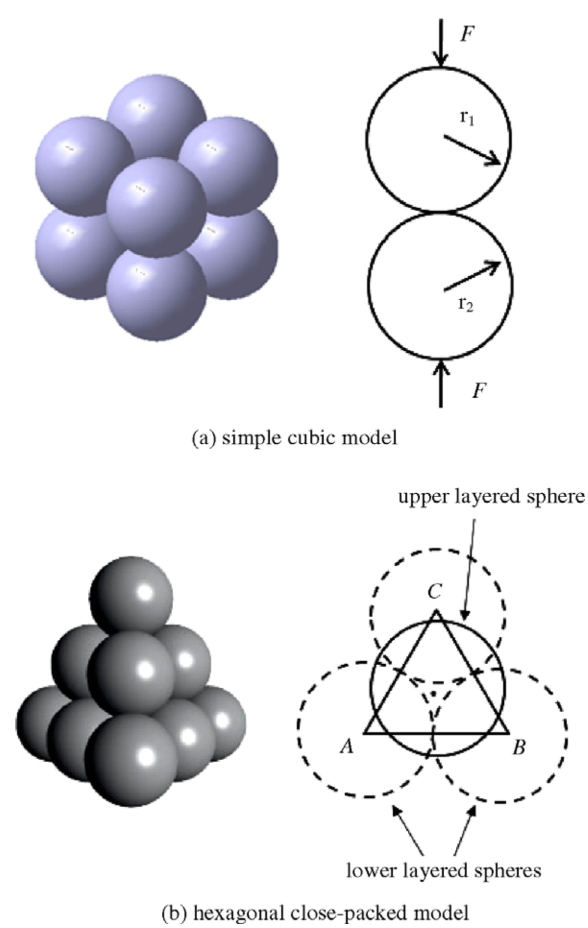

Fig. 1. Regularly packed sphere models.