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Investigation of radiative scattering effect of VIP filler materials using a novel statistical formulation

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ABSTRACT

Radiative heat transfer is investigated for each of isotropic and backward scattering patterns to evaluate the radiative thermal conduction of vacuum insulation panels (VIPs). As a means of analysis, a new statistical formulation is proposed and the results are compared with those of diffusion approximation, Monte Carlo method and discrete ordinate interpolation method (DOIM). The results of the statistical formulation agree well with those of Monte Carlo method and DOIM within 1% error, so that it may be regarded as an exact solution method. The results show that the insulation performance of the VIP can be enhanced by increasing the optical thickness or decreasing the wall emissivity. Also, the backward scattering is about twice effective than the isotropic scattering.

1. Introduction

Recently, vacuum insulation panels (VIPs) are regarded as the highly important thermal insulation component for buildings and refrigerators [1]. Especially, as the energy saving regulations have been reinforced, the usage of the VIPs is increasing instead of conventional insulators. It leads to considerable reduction of the insulation thickness and an increase in the available space of buildings and refrigerators because the VIPs have the thermal conductivity about one tenth that of conventional insulators such as glass wool and polyurethane foam [2].

VIP is generally composed of a filler material to sustain the external atmospheric pressure and an envelope to maintain the inner vacuum level. In the core of the VIPs, heat is thus transferred by the solid conduction through the filler material, the gas conduction through residual gas, and by the radiation. The gas conduction can be neglected in a high vacuum. The radiation is about one third of the total heat transfer of polyurethane foam and one fourth that of the glass fiber [2].

To improve the insulation performance of a VIP, therefore, it is important to understand the characteristics of radiative heat transfer through the filler material. Indeed, even for conventional insulators, radiative heat transfer is known to be important, especially at an elevated temperature [3,4]. For this reason, it has been investigated extensively for various media in the form of powders, foams and fibers. For the foam insulations, Glicksman et al. [5] experimentally measured the absorption and scattering coefficients as well as the phase function and they predicted the radiative heat transfer using the diffusion approximation. Kim et al. [6] measured the radiative properties of phenolic foams using FT-IR. For the fiber insulation, it was found that the radiative heat flux is affected by not only radiative properties but also mean radius of the fibers. It can be minimized by making the mean radius of the fibers close to that which yields the maximum extinction coefficient [7]. Also, when the fibers are oriented parallel to the boundaries, the radiation is effectively blocked [8]. Chu et al. [9] measured the effective thermal conductivity of ultra-fine powder insulations using a guarded-hot-plate apparatus and they compared the experimental results with those of diffusion approximation.

Further, it has been studied to find the way to decrease the radiative heat transfer. The opacified powders generally have lower radiative conductivity compared to un-opacified powders [10,11]. The fine opacified fibers provide high radiative thermal resistance due to their large extinction coefficients when the fiber size is small compared to the characteristic IR wavelength. Caps and Fricke [12] measured the thermal conductivity of opacified powder filler materials for vacuum insulation separately for conduction and radiation.

Recently, various methods are presented to predict the radiative heat transfer more accurately by considering scattering pattern. Sutton and Chen [13] presented a general integral method for non-homogeneous cylindrical media with anisotropic scattering.

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Nomenclature

A	absorption probability
E	emissive power, W/m^2
E_n	exponential integral function of order n
G	total strength of incident photons
H	height, m
I	radiation intensity, W/(m^2 sr^1)
k	thermal conductivity, W/(m K)
l	photon path length
P	probability function
q_r''	radiative heat flux, W/m^2
R_σ	random number for Monte Carlo method
R_0, S_0	probability variables for statistical formulation
s	coordinate along a line of sight, m
S	radiative source function, W/(m^2 sr^1)
T	temperature, K

Greek symbols

β	extinction coefficient, 1/m
ε	emissivity
θ	polar angle, rad
μ	direction cosine
ρ	reflectivity
σ	Stefan–Boltzmann constant, W/(m^2 K^4)
σ_s	scattering coefficient, 1/m
τ	optical thickness
τ_H	optical thickness for path length H
ϕ	azimuthal angle, rad

Subscripts

1, 2	surface 1 or 2
b	blackbody
bs	backward scattering
$diff$	diffusion approximation
IN	upstream point in discrete ordinate interpolation method
i	dummy counter
m	mean
P	grid point in discrete ordinate interpolation method
r	radiative
w	wall
μ	at a given direction cosine

Not only continuous change property but also step-change property problem can be solved by this method. Amiri et al. [14] modeled combined conductive and radiative heat transfer within the irregular geometries with absorbing, emitting, anisotropic scattering medium using the blocked-off method. Jinbo et al. [15] studied the relative errors caused by the approximation that linear and nonlinear anisotropic media are simplified to isotropic scattering ones using the finite volume method. They found that relative error of the isotropic scattering to anisotropic scattering is increased as the forward or backward scattering ratio increases. Jang et al. [16] predicted the radiative heat transfer in pure isotropic and backward scattering media using a Monte Carlo method and found that the backward scattering is more desirable in VIPs.

The objective of this study is to theoretically and numerically investigate the scattering effect of filler material on the insulation performance especially in cases of pure isotropic and backward scattering whereas it was just examined by numerical method in previous researches. To get exact solutions, a statistical formulation is proposed and compared with the Monte Carlo method, diffusion approximation and the authors' DOIM. The filler material is idealized as a one-dimensional pure scattering medium with diffuse walls. For various optical thicknesses and wall emissivities, the radiative conductivities are calculated and compared to find the effect of scattering mode on the insulation performance.

2. Problem definition and analysis

The filler material of the VIP is considered as a one-dimensional pure scattering medium between two walls (Fig. 1). Note that a purely absorbing/emitting medium such as opacifier-containing one can be treated as an isotropic scattering medium since the absorbed photons are later re-emitted in random directions. The medium is treated gray with a constant scattering coefficient σ_s. The temperatures of lower and upper walls are T_1 and T_2. Both walls are diffuse and have the same emissivity ε_w. There is only radiative heat transfer and the medium is at a radiative equilibrium in this study. Keep in mind, however, that conduction is frequently coupled with radiation in VIPs even at a moderate temperature.

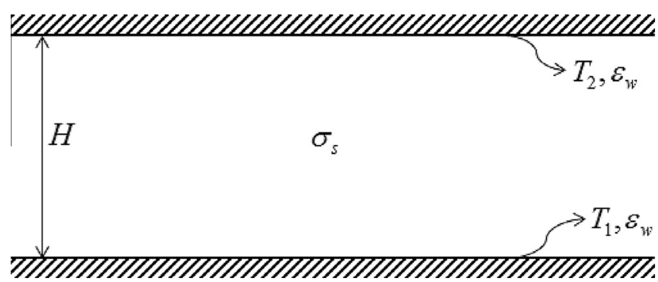

Fig. 1. Geometry of a one-dimensional pure scattering medium between two walls.

Most of the scattering patterns are very complicated. For dense irregular media, however, their random orientation can make the overall scattering fairly isotropic though individual particles may scatter anisotropically. On the contrary, the backward scattering mode can be realized by dispersing metal-coated flakes with their planes aligned parallel to the walls. For this scattering mode, the photon is always scattered to the opposite direction and its polar angle is not changed. It is indeed a kind of specular reflection.

This paper introduces a novel statistical formulation to treat these problems. However, as a means of verification, three other methods are briefly presented before the statistical formulation is described in detail.

2.1. Diffusion approximation

The diffusion approximation is commonly used to analyze the radiative heat transfer in a one-dimensional isotropic scattering medium because of its simplicity and convenience. However, it is not valid for an optically thin medium since the influence of the temperature jump near the boundaries can be dominant. In this case, this approximation may be modified using the jump boundary conditions. The final compact expression is obtained for a gray medium between parallel gray walls as [17],

$$k_{r,diff} = \frac{4\sigma T_m^3 H}{3\sigma_s H/4 + (2/\varepsilon_w - 1)}, \tag{1}$$