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Analysis of Combined Heat Transfer through the Core Materials of VIPs with Various Scattering Properties

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Abstract**—**Vacuum Insulation Panel (VIP) can achieve very low thermal conductivity by evacuating its inner space. Heat transfer in the core materials of highly-evacuated VIP occurs by conduction through the solid structure and radiation through the pore. The effect of various scattering modes in combined conduction-radiation in VIP is investigated through numerical analysis. The discrete ordinates interpolation method (DOIM) incorporated with the commercial code FLUENT® is employed. It is found that backward scattering is more effective in reducing the total heat transfer while isotropic scattering is almost identical with pure absorbing/emitting case of the same optical thickness. For a purely scattering medium, the results agrees well with additive solution with diffusion approximation, while a modified term is added in the effect of optical thickness to backward scattering is employed. For other scattering phase functions, it is also confirmed that backwardly scattering phase function gives a lower effective thermal conductivity. Thus the materials with backward scattering properties, with radiation shields are desirable to lower the thermal conductivity of VIPs.

Keywords**—**Combined conduction and radiation, discrete ordinates interpolation method, scattering phase function, vacuum insulation panel.

I. INTRODUCTION

INCREASED attention to CO_2-induced global warming and depletion of conventional energy resources invoke a need for a high performance thermal insulation. Accordingly, regulation on the insulation performance of façade becomes strengthened in many countries [1]. However, insulation performance of conventional insulation materials can hardly be improved, since their thermal conductivity cannot go down below thermal conductivity of air inside their porous structure.

Vacuum insulation panel (VIP) is a new insulation material whose inner space is evacuated to eliminate conduction by interstitial air. Usually, it is composed of an envelope and a core. The envelope packs the core structure to maintain the inner vacuum level and protects the core from the environmental gas permeation. Laminated Al-foil or metalized polymer film is commonly used as the envelope material [2]. The core withstands the external atmospheric pressure as well as suppresses the radiation and residual gas conduction with its porous structure. Porous materials with open cell structures such as glass fibers or polyurethane forms are commonly used as the core material.

In the core structure, heat is transferred by solid conduction through the core structure (responsible for k_s below), residual gas conduction (k_g), and radiation (k_r). The effective conductivity of VIP k_{eff} is often expressed as [2]

$$k_{eff} = k_s + k_g + k_r + k_{cpl} \tag{1}$$

Among them, the gas conduction is negligible in high vacuum. The coupling term k_{cpl} appears when there is interaction between different heat transfer modes. Heat transfer by solid conduction and radiation through porous materials has been investigated widely. Amount of solid conduction in VIP is dependent on the structure and packing density of the porous core materials. Kwon et al. [3] calculated and reviewed the solid conductivity for typical core materials and artificial structures. The radiative conductivity of porous material is often given by the diffusion approximation [4]

$$k_r = \frac{16\sigma T_m^3}{3\beta} \tag{2}$$

where β is the Rosseland mean extinction coefficient. These coefficients can be obtained by integrating the spectral transmittance [5]. Typical values of β for porous materials used in VIPs ranges from 3,000 to 50,000 m-1 [3], [6], which gives k_r=0.2 to 3 mW/m-K in 300K. When loose layers of porous material should be considered or partly transparent material is employed, radiation can account for significant amount of overall heat transfer. It can be suppressed by employing radiation shields [7] or adding absorbing or scattering particles like carbon particles, which are frequently called “opacifiers” [8].

The combined heat transfer in VIPs is not treated much, possibly due to the complexity of the analysis. However, conduction and radiation apparently interact significantly with each other in VIPs, where amount of heat transfer by these heat transfer modes range in a similar order. Analysis on combined conduction and radiation has been applied in studying optically thin porous materials [9], [10] and multilayer insulations [11]. For vacuum insulation panels, Lee et al. [12] studied combined heat transfer through interstitial materials of VIPs. It is found that the performance of radiation shields as a parts of the core structure can be affected significantly by the optical thickness of the interstitial filler material and amount of contact

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resistance.

In this paper, the scattering phenomena in the combined conduction-radiation in vacuum insulation panels will be investigated to enhance the insulation performance. Representatively, two extreme scattering properties are examined; isotropic scattering and backward scattering. The effect of isotropic and backward scatterings in a purely scattering medium has been studied by using Monte Carlo method [13]. It has been found that the radiative thermal resistance of the backward scattering medium is about twice as large as that of the isotropic one when the medium is optically thick. In this study, the effects of various scattering modes on the insulation performance of VIPs are investigated when combined heat transfer is present. The analysis will be conducted with the discrete ordinate method interpolation method (DOIM) incorporated with the commercial code FLUENT®. The effects of scattering albedo and scattering phase functions of the core material, as well as its optical thickness and emissivity at the boundary, on the effective thermal conductivity of VIPs are examined.

II. Modeling and Analysis

A. Numerical Scheme

VIP is normally a thin panel whose thickness is a few tens of millimeter. The conduction through the envelope at the edge may contribute significantly to the amount of total heat transfer. For the sake of simplicity, we exclude this edge effect and only consider the heat transfer through the core material. So the core material in VIP is modeled as a 1-D plane-parallel medium.

The core material is assumed to have constant thermal and radiative properties. Two walls are isothermal at different temperatures T_{B0} and T_{U0}. Both walls are diffuse and have an emissivity ε_w. There is both conductive and radiative heat transfer and the medium is at thermal equilibrium. The physical model of VIP is depicted in Fig. 1.

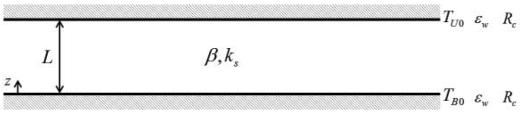

Fig. 1 Physical model of VIP used in this study

The energy equation with constant thermal conductivity k_s can be expressed as

$$k_s \nabla^2 T - \nabla \cdot \vec{q}_R = 0 . \tag{3}$$

Here, the radiative heat source term $\nabla \cdot \vec{q}_R$ is given by [5]

$$\nabla \cdot \vec{q}_R = 4\kappa \left(\sigma T^4 - \frac{1}{4} \int_{4\pi} I d\Omega \right), \tag{4}$$

where κ is the absorption coefficient.

The radiative transfer equation (RTE) and its boundary condition for gray plane-parallel medium with diffuse walls is expressed as [5]

$$\frac{1}{\mu} \frac{dI}{\beta dz} = (1-\omega) I_b - I + \frac{\omega}{4\pi} \int_{4\pi} I(\Omega') \Phi(\Omega', \Omega) d\Omega' , \tag{5}$$

$$I_w^+(\Omega) = \varepsilon_w I_{bw} + \frac{1-\varepsilon_w}{\pi} \int_{\hat{n} \cdot \hat{s}' < 0} I(\Omega') \left| \hat{n} \cdot \hat{s}' \right| d\Omega' , \tag{6}$$

where μ is the directional cosine, $\omega = \sigma_s / \beta$ is the scattering albedo and $\Phi(\Omega', \Omega)$ is the scattering phase function of the medium. Equations (3) and (5) are nonlinear integro-differential equations and the numerical analysis is needed. The total heat flux q''_{tot}, which is the sum of radiative and conductive heat fluxes, at the centerline is used to determine the effective thermal conductivity of the core using the relation

$$k_{eff} = q''_{tot} L / (T_{B0} - T_{U0}) . \tag{7}$$

To solve the problem, the DOIM incorporated with the commercial code FLUENT® is used. The DOIM is a modified version of the discrete ordinates method (DOM) using an interpolation scheme to analyze radiative transfer problems [14]. Recently, the DOIM is incorporated into commercial code FLUENT® and proved to be successful in analyzing various combined heat transfer problem [15].

A two-dimensional rectangular enclosure with control volumes of 20x10 (meaning a grid system of 21x11) is used in the simulation. The domain is stretched 10 times in the horizontal direction compared with the vertical direction. Symmetric boundary conditions are given for the side walls.

As stated above, conduction and radiation are often considered separately in the analysis of insulation materials. The effective thermal conductivity for an additive is represented as [16]

$$k_{eff} = k_s + \frac{4\sigma T_m^3 L}{3\tau_L / 4 + (2/\varepsilon_w - 1)} , \tag{8}$$

where $\tau_L = \beta L$ is the optical thickness of the medium.

B. Scattering in the Medium

Electromagnetic wave or photon would be scattered by small particles or structures in the medium. Scattering phenomena has been extensively studied [5]. In the radiative transfer equation (5), scattering of incident radiation is expressed by the term $\frac{\omega}{4\pi} \int_{4\pi} I(\Omega') \Phi(\Omega', \Omega) d\Omega'$. Scattering phase function $\Phi(\Omega', \Omega)$ relates amount of outgoing intensity to direction Ω with the amount of incident radiation coming from the direction Ω'.

For isotropic scattering, incoming radiation is scattered in all direction uniformly and the scattering phase function is given by $\Phi(\Omega', \Omega) = 1$. When radiative equilibrium is assumed for a gray medium, it is identical with the absorption and emission process. When radiation occurs in conjunction with other heat transfer modes, heat transfer characteristics of isotropic scattering medium is not the same with that of absorbing and emitting medium, however [17].

In a perfect backward scattering medium, the medium reflects the incoming radiation to opposite direction (from μ to $-\mu$). This scattering property can be approximately realized by inserting horizontal shiny flakes in the medium.

In addition to these two scattering modes, more scattering functions are examined here. Scattering functions F1, F2, B1, B2, derived from Mie theory, are taken from Kim and Lee [18]. Linear anisotropic functions, which are expressed as [5]

$$\Phi(\Omega,\Omega') = 1 + a_1(\Omega \cdot \Omega'), \tag{9}$$

are also examined with coefficient a_1=1 and -1. Their phase functions are drawn in Fig. 2.

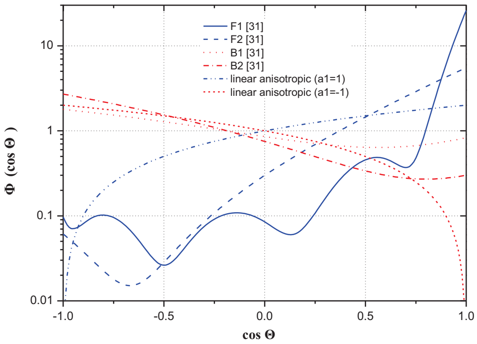

Fig. 2 Scattering phase functions

III. RESULT AND DISCUSSION

The effective thermal conductivities are calculated for various cases with a fixed solid conductivity. Solid conductivity of VIP is 1 to 3mW/m-K [2]; 1 mW/m-K is taken here. The mean temperature is 300 K with T_{B0}=310 K and T_{U0}=290 K. The height L is 0.01 m.

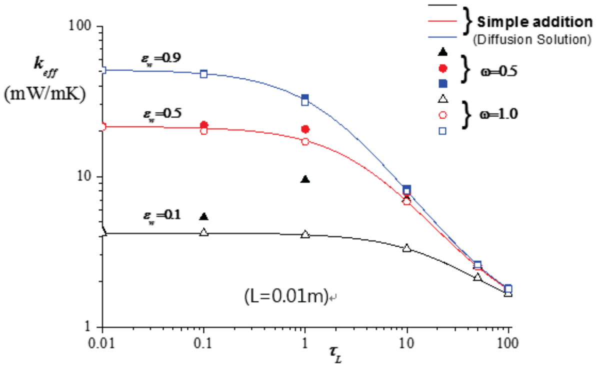

Fig. 3 The effective thermal conductivities for isotropic scattering medium with ω=0.5 and ω=1.0.

Fig. 3 shows the effective thermal conductivity k_{eff} of absorbing, emitting and isotropic scattering medium for various optical thicknesses, wall emissivities, and scattering albedos. The results are compared with the simple additive solution given by (8).

TABLE I
THE COMPARISON OF EFFECTIVE THERMAL CONDUCTIVITIES BETWEEN VARIOUS SCATTERING PHASE FUNCTIONS

ε_w=1.0 , $\sigma_s H$=100	k_{eff}(mW/m·K)		
	ω=0.0	ω=0.5	ω=1.0
Isotropic	1.80	1.80	1.81
pure backward	1.80	1.54	1.42
F1	1.80	2.08	2.68
F2	1.80	2.30	4.85
B1	1.80	1.72	1.67
B2	1.80	1.65	1.56
linear anisotropic(a_1=+1)	1.80	2.05	2.55
linear anisotropic(a_1=-1)	1.80	1.66	1.57

As discussed in previous research, for nonscattering case (ω=0.0), the computed effective thermal conductivities are significantly larger than that predicted by the additive approximation for low emissivity boundaries in the intermediate optical thickness range. Reduction of the effective thermal conductivity at the low emissivity walls becomes marginal as can be seen from the combined analysis. Large temperature slip, which appears in the pure radiation case with low emissivity boundaries [19], leads to enhanced conduction near the wall through large temperature gradient for combined analysis. On the other hand, when the medium is optically thick (r_L»1), the value of the effective thermal conductivity approaches to that for the black wall regardless of actual wall emissivities.

For the cases with scattering, there is little change in k_{eff} when the scattering albedo ω is 0.5 while the thermal conductivity approaches to that by the simple additive solution when ω=1.0. It is noteworthy that isotropic scattering material is analogous to absorbing/emitting medium of the same optical thickness. Further investigation is required to predict the behavior of medium with very high scattering albedo such as glass fiber.

On the other hand, by observing the general trends in Fig. 3, the effect of optical thickness and wall emissivity can be found. The radiative resistance of optical thickness, which is represented by the term $3\tau_L/4$ in the denominator of (8), decreases the effective thermal conductivity. When the medium is purely scattering, the effective thermal conductivity is significantly affected by the wall emissivity even when the optical thickness of the medium is much higher than 1.

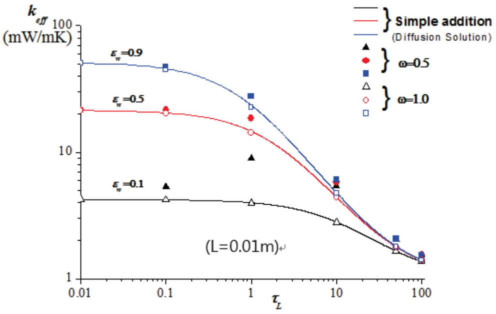

Fig. 4 The effective thermal conductivities for backward scattering medium ith ω=0.5 and ω=1.0

Fig. 4 shows the effective thermal conductivity for backward scattering medium. Additive approximation is obtained with a modified diffusion approximation for such scattering medium [13]. Compared with isotropically scattering case, smaller values are obtained and this trend is more obvious when the medium is optically thick. Also, the effective thermal conductivity decreases with increasing scattering albedo ω, whereas its dependence on ω is not so significant for isotropic scattering. So adding particles with highly backward scattering is more effective in reducing k_{eff}. Jang et al. [13] showed that backward scattering is twice as much effective as the isotropic scattering for pure scattering medium. They represented this effect by replacing $3\tau_L / 4$ in the denominator of 2nd term in (8) by $3\tau_L / 2$.

In addition to isotropic and backward scattering, other phase functions are tested for $\tau_L = 100$ and $\varepsilon_w = 1.0$. The resulting k_{eff} is shown in Table I. As anticipated, scattering phase function with more backward component is more effective in reducing the heat transfer. Another noticeable fact is that the k_{eff} increases more rapidly with scattering albedo for forward scattering functions, while the decrease in k_{eff} for backward scattering medium between ω=0.5 and 1.0 is smaller than that between ω=0 and 0.5.

In summary, the insulation performance of the core material can be enhanced by increasing optical thickness by adding some radiation-blocking materials. Backwardly scattering medium can block radiation more than isotropic scattering ones. Low emissivity radiation shields also can decrease the effective thermal conductivity when the medium is almost purely scattering or some backward scattering exists.

IV. CONCLUSION

In this study, an analysis on the combined conduction-radiation for the core materials of VIPs with various scattering properties is conducted, using the discrete ordinate interpolation method incorporated into the commercial code FLUENT®.

The effective thermal conductivities are calculated for a solid conductivity of 1mW/m-K and various optical thicknesses and wall emissivities. It is found that the additive solution may yield significantly erroneous prediction. As anticipated, combined analysis for absorbing/ emitting medium, which is conducted with zero scattering albedo, gives larger effective thermal conductivity of core materials than that of additive solution. Especially, the effect of wall emissivity was significantly reduced for larger optical thicknesses. Isotropically scattering medium behaves similarly with non-scattering medium unless it is almost purely scattering. Isotropically scattering medium behaves similarly with the non-scattering medium with same optical thickness when the scattering albedo of the medium is not very large. On the other hand, the amount of heat transfer rate is smaller for backward scattering than for isotropic scattering. Also, backward scattering is effective when scattering albedo is not very large. In conclusion, the materials having large scattering albedo and larger optical thickness, along with backwardly scattering properties are recommended to be used as the core or insertion material to have lower effective thermal conductivity of VIPs.

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