A Comprehensive Review on Thermal Radiation of Open Cellular Porous Materials

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***Abstract* – The radiative heat transfer in highly porous materials, open cellular structure or open-celled foam, is reviewed to characterize the radiative transport process in terms of fundamental radiative properties such as extinction coefficient (β), albedo (ω) and scattering phase function :$P(cos\theta)$. Firstly, the geometric shape and topology of open-celled foam are deeply presented. Thereafter, the governing equation for radiative transfer (RTE) and the solution methods are represented. Finally, analytical expressions relating such radiative properties to basic structural parameters developed through mathematical modeling and experimental studies are briefly recalled and discussed.**

Keywords – Radiative Heat Transfer, Open –Cellular Porous Material, Extinction Coefficient

1. INTRODUCTION

The thermal transport consisting of conduction, convection and radiation in highly porous, cellular foams with open cells have been studied extensively in recent years [1-6]. The motivation is attributed to their high surface area to volume ratio as well as enhanced flow mixing capability due to high tortuosity. From this reasons, open-celled foams have been proposed for many applications such as porous tissue engineering scaffolds [9,10], hydrogen storage technologies [11], solar energy storage [12], electrochemical cells [13] and radiant porous burner [14, 15]. Regarding to three mode of heat transfer, [1] thermal radiation is a dominant mode in many high temperature systems. Understanding of radiative transfer in porous materials is important for design, operation and simulation of the energy conversion and utilization systems. However, it is particularly difficult to estimate radiative heat transfer in solid foams due to the complexity of the architecture. In order to improve the accurate prediction and operation of open-celled foam, the radiative properties of dispersed media is employed [16, 17]. Commonly, three techniques are used to predict the radiative properties of dispersed media: geometric law, transmittance measurement technique and X-ray tomography method. For the first technique, the porous structure equivalent to a random arrangement of particles of given shapes is considered and the Mie theory or the geometric optics laws is conducted [18-20]. The second technique is based on reflectance and transmittance measurements of the medium and the inverse method is operated [21, 22]. Finally, the real complex structures of the porous medium using the X-Ray tomography method and Monte Carlo simulation at the local microscopic scale are performed [23, 24]. However, Monte Carlo simulations in tomographed samples are not convenient in practice because it require a gigantic computational effort.

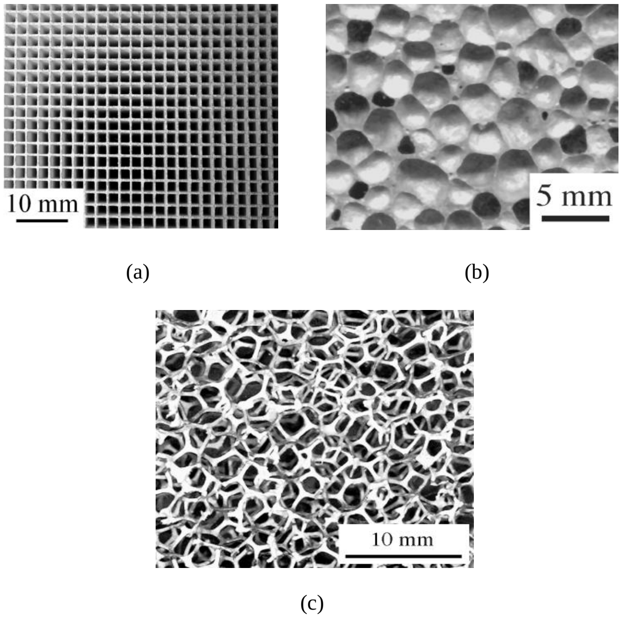
Among the radiative properties, it is particularly interesting to evaluate the extinction coefficient (β) because it is a local property, i.e., the scattering (σ) and absorption coefficient (κ) are presented simultaneously in the extinction coefficient ($\beta = \kappa + \sigma$). Usually, the extinction coefficient depends on the porosity (ϕ) and on the morphological structure of the foam. In addition, several studies of radiative properties of open cellular porous medium pay attention to the scattering phase function ($P(\cos\theta)$) and the albedo (ω) [17, 19, 25, 26].

From above observation, the aim of the present article is to review the experimental and theoretical studies of the fundamental radiative properties consisting of extinction coefficient (β), albedo (ω) and scattering phase function ($P(\cos\theta)$) in an open cellular porous material. To deeply gain understanding in characteristics of the radiative transport process of the open-celled foam, the geometry of this material is also discussed in the first part of the present article.

2. OPEN CELLULAR GEOMETRY

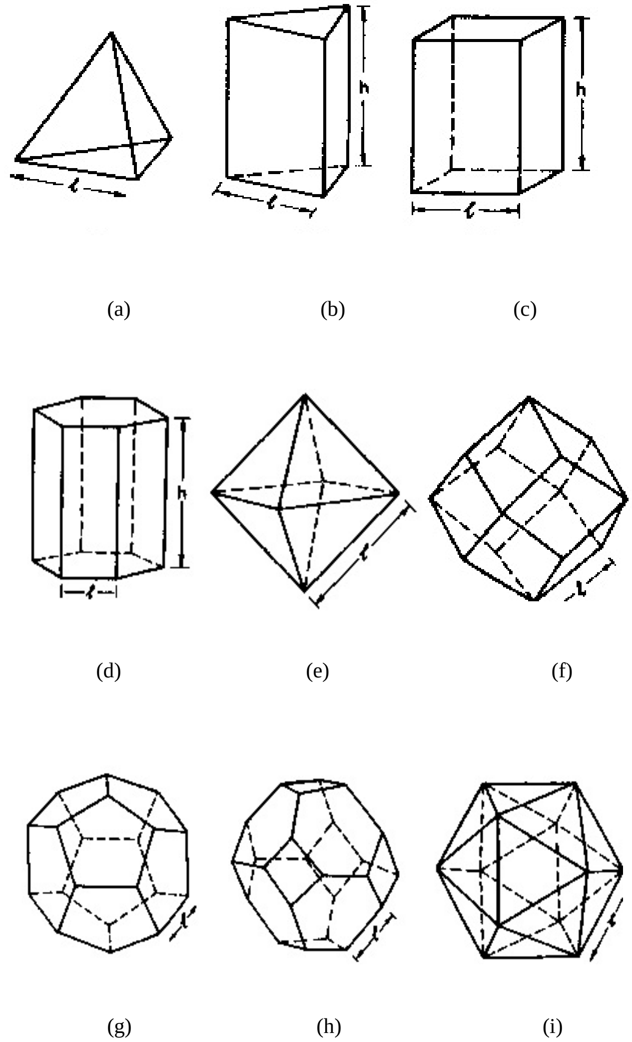
A cellular solid [27] is one made up of an interconnected network of solid struts or plates which from the edges and faces of cells, in which three typical structures are shown in Figs. 1 [28]. As seen from Fig. 1(a), the simplest structure is a two-dimensional array of polygons which pack to fill a plane area like the hexagonal cells of the bee; and for this reason this two-dimensional cellular materials is called as *honeycombs*. More commonly, the cells are polyhedral which pack in three dimensions to fill space; thus three-dimension cellular materials *foams* are defined as shown in Figs. 1(b) and 1(c). The foam is said to be *closed-celled*

(Fig.(b)), because the faces of each cell, of which are solid too, is sealed off from its neighbors. Figure 1(c) is said to be *open-celled*, if the solid of which the foam is made by containing in the cell edges only (so that the cells connect through open faces); and of course, some foams are partly open and partly closed.



Figures 1 Microstructures of (a) a two-dimensional honeycomb, (b) a three-dimensional closed-cell foam and (c) a three-dimensional opened-cell foam.

Regarding to above definitions, the present article elaborate on open-cell foam; thus the geometry and characteristics of the open-cell foam is discussed here in more depth. The unit cell which pack to fill space in three dimensions are sketched in Fig. 2 [27], which shows the shapes available for packing together to fill space; their geometries are characterized in Table 1 [27].

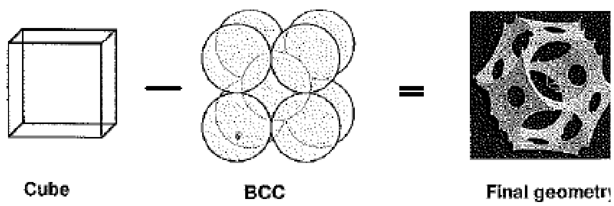


Figures 2 Three-dimensional polyhedral cells: (a) tetrahedron, (b) triangular prism, (c) rectangular prism, (d) hexagonal prism, (e) octahedron, (f) rhombic dodecahedron, (g) pentagonal dodecahedron, (h) tetrakaidecahedron and (i) icosahedrons.

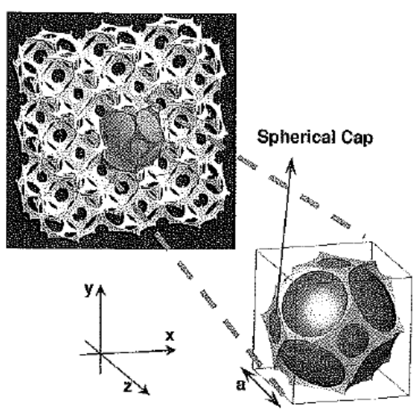
Table 1 Geometric properties of isolate cells [27]

Cell shape	**Number of faces, f**	**Number of edges, n**	**Number of vertices, v**	**Cell volume**	**Surface area**	**Comments**
Tetrahedron	4	6	4	$0.188l^3$	$\sqrt{3}l^2$	Regular
Triangular Prism	5	9	6	$(\sqrt{3}/4)\, l^3 A_t$	$\sqrt{3}l^2/2\left(1+2\sqrt{3}A_t\right)$	Packs to fill space
Rectangular Prism	6	12	8	$l^3 A_t$	$2l^2\left(1+2A_t\right)$	Packs to fill space
Hexagonal Prism	8	18	12	$(3\sqrt{3}/2)\, l^3 A_t$	$\sqrt{3}l^2\left(1+2\sqrt{3}A_t\right)$	Packs to fill space
Octahedron	8	12	6	$0.471l^3$	$3.46l^2$	Regular
Rhombic Dodecahedron	12	24	14	$2.79l^3$	$10.58l^2$	Packs to fill space
Pentagonal Dodecahedron	12	30	20	$7.663l^3$	$20.646l^2$	Regular
Tetrakaidecahedron	14	36	24	$11.31l^3$	$26.80l^2$	Packs to fill space
Icosahedrons	20	30	12	$2.182l^3$	$8.660l^2$	Regular

In the approach for foam geometry creation, conventionally, the shape of the pore is assumed to be spherical and spheres of equal volume (unit cell) are arranged according to the lattice structures of the *body-centered cubic* (BCC) lattice [29]. The foam unit cell geometry is obtained by subtracting the unit cell cube from the spheres at the various lattice points as shown in Fig. 3(a). The cross-section of the foam ligaments is a set of convex triangles (plateau borders), all of which meet at symmetric tetrahedral vertices. It may be noted that there is a no uniform distribution of material mass along the length of the ligament with more mass accumulating at the vertices (nodes) resulting in a thinning at the center of the ligament. A schematic illustration of the foam geometry in BCC unit cell is shown in Fig. 3(b).



(a)



(b)

Figures 3 Schematic of (a) the representation of foam geometry creation in the body-centered cubic structure (BCC) and (b) a foam geometry in BCC unit cell

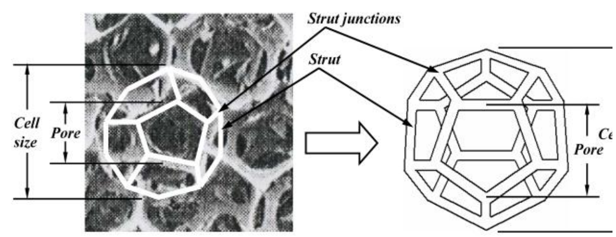
To simply clarify the geometry of open cellular porous material (or open-celled foam), a shape of this materials referred from Fig. 2 can be arranged as *three-dimensional pentagonal dodecahedron* which a perspective view is depicted in Fig. 4 [30]. The open-celled foam consists of three-dimensional dodecahedron-like cells with pentagonal or hexagonal open-cell walls, where a pentagonal dodecahedron cell is illustrated as a typical example. For this material, it is difficult to specify a pore shape or size, and thus two quantities, i.e., the *porosity* (ϕ) and the pore density, are used to describe the material.

Porosity (ϕ) or void fraction is a measure of the void (empty) spaces in a material, and is a fraction of the volume of voids over the total volume, between 0-1, or as a percentage between 0-100%. The porosity of porous medium describes the fraction of void space in the material. It is defined by the ratio following as:

$$\phi = \frac{V_V}{V_T}, \tag{1}$$

where V_V is the volume of void-space (such as fluids) and V_T is the total or bulk volume of material. The porosity of commercially available open-celled foams is typically about 0.8 – 0.95 [8, 19, 25].

The pore density is the number of pores present per unit length of the material, typically expressed in unit of *pore per inch* (PPI), and is roughly constant in the three directions. Usually the number of pores is sufficiently large.



Figures 4 Perspective view of a pentagonal dodecahedron for open-cellular porous materials.

3. Radiative Heat Transfer Equation

3.1 Continuum Treatment for Radiative Transfer

The fundamentals of radiation heat transfer in participating media (absorbing, emitting and scattering media) have been given by many classical text books [31-34]. Their approach treats the solid-fluid phases as a single continuum. Therefore, heterogeneous, solid and fluid phases are presented simultaneously, differential element is applied. The open-celled foam is also characterized as heterogeneous participating media and thus can be treated as a continuum for purposes to describe the propagation of radiative intensity through the medium. In the continuous approach, the radiative heat transfer equations (RTE) are derived by using the principle of energy conservation. This approach is acceptable if the size of the system is much larger than the wavelength of the radiation. In general, the assumptions of randomness, homogeneity, and continuity are implied in the formulation. Homogeneity is essential for the medium to be treated as a continuum. A dispersed medium may be considered homogeneous if particle diameters are small compared with the medium thickness. This approach yields the classical RTE which is used for most radiative heat transfer problems in absorbing, emitting and scattering media. The RTE can be formally derived by making a radiative energy balance on a differential volume element along a single line of sight. It is an integro-diferential equation that may be written in terms of the spectral intensity I_λ of radiation propagating in a direction Ω as:

$$\frac{dI_\lambda(\Omega)}{ds} = -(\sigma_\lambda + \kappa_\lambda) I_\lambda(\Omega) + \kappa_\lambda I_{b\lambda} + \frac{\sigma_\lambda}{4\pi} \int_{4\pi} I_\lambda(\Omega) P_\lambda(\Omega' \to \Omega) d\Omega', \quad (2)$$

where σ_λ and κ_λ are the scattering and absorption spectral volumetric coefficients, respectively, and $I_{b\lambda}$ is Planck's blackbody function and $d\Omega$ is an elemental solid angle surrounding the direction Ω. The spectral scattering phase function $P_\lambda(\Omega' \to \Omega)$ represents the probability that the radiation propagating in a direction Ω' is scattered in the direction Ω. The phase function is normalized such that

$$\frac{1}{4\pi} \int_{4\pi} P_\lambda(\Omega' \to \Omega) d\Omega = 1 \cdot \quad (3)$$

Commonly, the total attenuation of spectral intensity I_λ by both absorption and scattering is known well as extinction (β_λ) [31, 33]. Thus, an extinction coefficient is defined by

$$\beta_\lambda = \kappa_\lambda + \sigma_\lambda \cdot \quad (4)$$

Here, κ_λ and σ_λ are spectral absorption and spectral scattering coefficient, respectively. Moreover, the scattering albedo (ω_λ) is generally employed as given by

$$\omega_\lambda = \frac{\sigma_\lambda}{\kappa_\lambda + \sigma_\lambda} = \frac{\sigma_\lambda}{\beta_\lambda} \cdot \quad (5)$$

After introducing the extinction coefficient defined in Equation (4), one may be restate equation (2), RTE, in its quasi-steady from as:

$$\frac{dI_\lambda(\Omega)}{ds} = -\beta_\lambda I_\lambda(\Omega) + (1-\omega_\lambda)\beta_\lambda I_{b\lambda} + \frac{\omega_\lambda \beta_\lambda}{4\pi} \int_{-1}^{1} I_\lambda(\Omega) P_\lambda(\Omega' \to \Omega) d\Omega' \cdot \quad (6)$$

The last two term in Equation (6) are often combined and are then known as the *source function* for radiative intensity,

$$S_\lambda(\Omega) = (1-\omega_\lambda)\beta_\lambda I_{b\lambda} + \frac{\omega_\lambda \beta_\lambda}{4\pi} \int_{-1}^{1} I_\lambda(\Omega) P_\lambda(\Omega' \to \Omega) d\Omega' \cdot \quad (7)$$

Finally, Equation (6) becomes

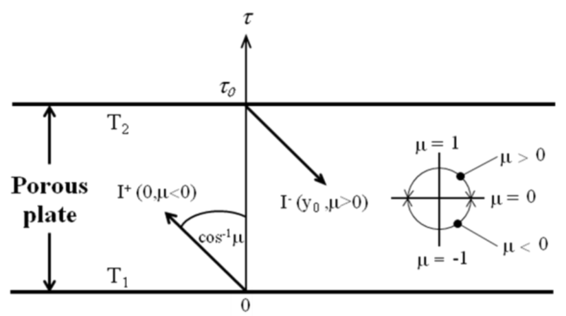
$$\frac{dI_\lambda(\Omega)}{ds} + \beta_\lambda I_\lambda(\Omega) = S(\Omega) \cdot \quad (8)$$

This equation only involves three the spectral radiative properties of the medium, extinction coefficient, albedo and phase function. These properties are those of a pseudo-continuous medium equivalent in terms of radiative transport, to the real dispersed material.

3.2 Solution of RTE

In general, a solution of the radiative heat transfer equation (RTE) has been solved by two directions: exact and approximated solution method. Both methods may be placed into four different categories: 1) Geometry, 2) Temperature Field, 3) Scattering and 4) Radiative properties. A more details of these categories are discussed as following:

1) Geometry in the radiation problem may be one-dimensional, two-dimensional or three-dimensional. Most investigations to date have dealt with one-dimensional geometries, and the vast majority of these dealt with the simplest case of a one-dimensional plane-parallel slab as shown in Fig. 5 [31].



Figures 5 Coordinates for solution of RTE for a plane-parallel slab.

2) The least difficult situation arises if the temperature profile or temperature field within the medium is known, making Equation (6) a relatively simple integral equation. Consequently, the most basic case of an isothermal medium has been studied extensively. Alternatively, if radiative equilibrium prevails, the temperature field is unknown but uncoupled from conduction and convection, and must be found from directional and spectral integration of RTE. In the most complicated scenario, radiative heat transfer is combined with conduction and/or convection, resulting in a highly nonlinear integro-differential equation.

3) The solution to a radiation problem is greatly simplified if the medium does not scatter. In that case the equation of transfer reduces to a simple first-order differential equation if the temperature field is known. In scattering case, the isotropic scattering is often assumed. Relatively few investigations have deal with the case of anisotropic scattering, and most of those are limited to the case of linear-anisotropic scattering.

4) Although most participating media display strong nongray character, the vast majority of investigations to date have centered on the study of gray media. In addition, while radiative properties also generally depend strongly on temperature, concentration, etc., most calculations are limited to situations with constant properties.

The exact analytical solution of RTE in homogeneous participating media, in which here focuses on the open-celled foam, are difficult resulting from an integro-differential equation of radiative intensity in five independent variables, including of three space coordinates and two directions coordinates [31].

Therefore, most exact solutions are limited to simplest case dealing with a one-dimensional plane-parallel gray media; it is isothermal or at radiative equilibrium and the scattering radiation is usually isotropic, if scatter is considered [32]. From this simplest case, the RTE or Equation (6) becomes

$$\mu \frac{dI_\lambda(\tau,\mu)}{d\tau} + I_\lambda(\tau,\mu) = S_\lambda(\tau,\mu), \tag{9}$$

Here μ is the cosine of angle θ between the direction Ω and οτ direction, τ is optical thickness and $S_\lambda(\tau, \mu)$ represented as the source function. Theses parameters are defined as

$$d\tau = \beta_\lambda ds,$$

$$\tau = \int_0^s \beta_\lambda ds', \tag{10}$$

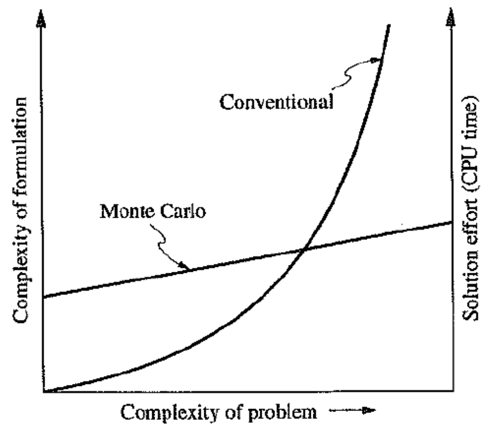
$$S_\lambda(\Omega) = (1-\omega_\lambda) I_{b\lambda} + \frac{\omega_\lambda}{2}\int_{-1}^{1} I_\lambda(\tau,\mu') P_\lambda(\mu,\mu') d\mu' . \tag{11}$$

$$P_\lambda(\mu,\mu') = \sum_{n=0}^{N} a_n P_n(\mu) P_n(\mu'), \tag{12}$$

$$a_0 = 1, \tag{13}$$

where $P_n(\mu)$ and $P_n(\mu')$ are the Legendre polynomial of order n and argument μ and μ' [31]. The phase function $P_\lambda(\mu, \mu')$ is independent of the azimuthal angle

In the past of a few decades, several approximated solutions of RTE are devised, but the majority of radiative heat transfer analyses today appear to use one of four methods [30]: 1) The spherical harmonics method or a variation of it; 2) The discrete ordinate method or its more modern form; 3) The zonal method; 4) The Monte Carlo method. By comparing the first two approximation methods, in the simplification, the spherical harmonics method is more simplifier than the discrete ordinate method because the RTE can be reformed to simple partial differential equations and accuracy improves only slowly for higher-order approximations while mathematical complexity increases extremely rapidly. The last two approximate methods are elaborate schemes and more difficult than the first two approximation with the simplified problems of radiative transfer, particular in Monte Carlo technique. Figure 6 shows the comparison of Monte Carlo and conventional solution methods [33]. As the complexity of the problem increase, however, the complexity of formulation and solution effort increase much more rapidly for conventional techniques. For problems beyond a certain complexity, the Monte Carlo solution will be preferable. Unfortunately, there is no way to determine a piori precisely where this crossover point in complexity lies. The disadvantage of Monte Carlo method is that they are subject to statistical error.



Figures 6 Comparison of Monte Carlo and conventional solution methods.

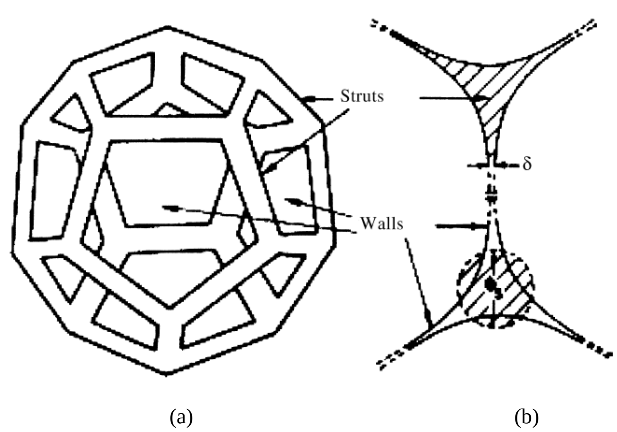
4. THERMAL RADIATIVE PROPERTIES

The extinction coefficient β, albedo ω and scattering phase function $P(\cos\theta)$, which appear as parameters in RTE, are the radiative properties need for radiative transfer calculations in participating media (Open-cellular porous media). Several attempts to model and to measure the radiative properties of complex open-cellular porous media have been made.

Glicksman and Torpey [35] considered foam (Open-cellular) as a set of randomly oriented black-body struts and used an extinction coefficient in single-particle properties form of unity. They neglected scattering by struts. The strut cross-section was constant and occupied two-thirds of the area of an equilateral triangle formed at the vertices (Fig. 7). The resulting mean extinction coefficient β is a function of the cell diameter d, the foam density ρ_f, and solid polymer density ρ_s as given by

$$\beta = 4.10 \frac{\sqrt{f_s \rho_f / \rho_s}}{d}, \tag{14}$$

where f_s is the fraction of solid material in the strut.



Figures 7 Dodecaeder model for a foam cell: (a) perspective view; (b) cross-section through struts and walls

Hsu and Howell [36] presented a semi-empirical formula of the effective extinction coefficient β (m^{-1}) as a function of actual pore size (D_m) in mm:

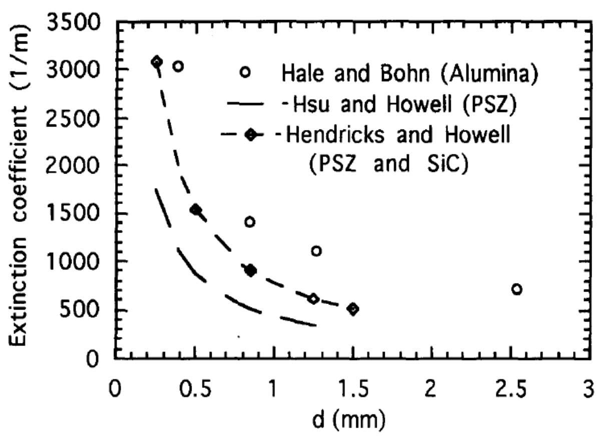
$$\beta = \frac{3(1-\phi)}{D_m}. \quad (15)$$

They claimed that Equation (15) is applicable to pore diameter greater than 0.6 mm.

Hendricks and Howell [37] found that a modified geometrical optics relation fits the data for the integrated extinction coefficient of both zirconia (PS ZrO_2) and silicon carbide (SiC) and recommended the following relations

$$\beta = \frac{\Psi(1-\phi)}{D_m}, \quad (16)$$

where the parameter Ψ are 4.4 for PS ZrO_2 and 4.8 for SiC. Moreover, the correlations of extinction coefficient of Hendricks and Howell [37] were compared to Hsu and Howell [36] data and the Hale and Bohn [38] along with the 488 nm data as shown in Fig. 8.



Figures 8 Extinction coefficient vs. pore diameter for various reticulated ceramics.

Two dual-parameter phase functions were investigated for the materials: one based on the physical structure of open-cellular porous ceramics and the other on a modified Henyey-Greenstein phase function. The first is a linear combination of a di!raction-dominated phase function (P_{diff}), an isotropic phase function, and a back-scattering phase function ($P_{dif,ref}$), taking the mathematical form:

$$P_\lambda(\theta) = f_{isen,\lambda} + \left(1 - f_{isen,\lambda} - f_{back,\lambda}\right) P_{diff}(\theta) + f_{back,\lambda} P_{dif,ref}(\theta). \quad (17)$$

The second phase function was a modified Henyey-Greenstein phase function given by the mathematical expression:

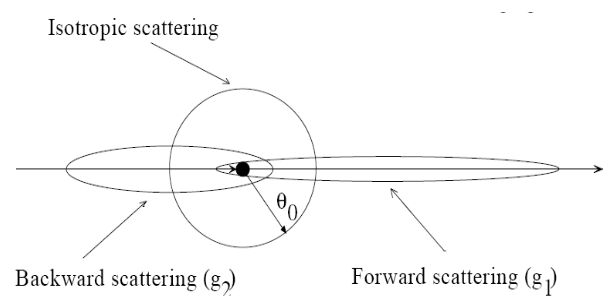
$$P_\lambda(\theta) = f_{isen,\lambda} + \left(1 - f_{isen,\lambda}\right) P_{HG,\lambda}(\theta), \quad (18)$$

where $P_{HG,\lambda}$ is the Henyey-Greenstein phase function and given by [33]

$$P_{HG,\lambda}(\theta) = \frac{1-g_\lambda^2}{\left(1+g_\lambda^2+2g_\lambda\cos\theta\right)^{3/2}}. \quad (19)$$

Here g_λ is parameter of Henyey-Greenstein phase function.

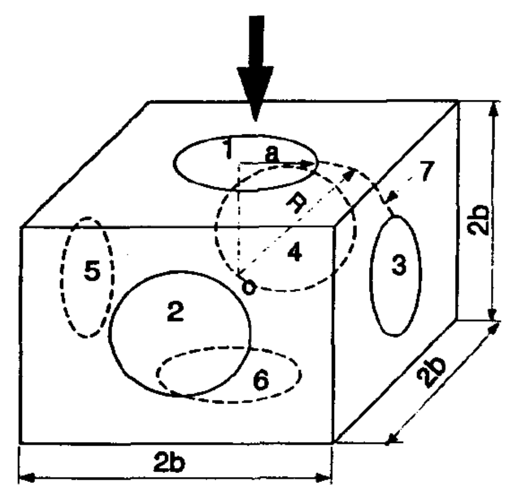
To clarify the understanding in this phase function, the composed of Henyey-Greenstein phase function [39] is shown in Fig. 9.



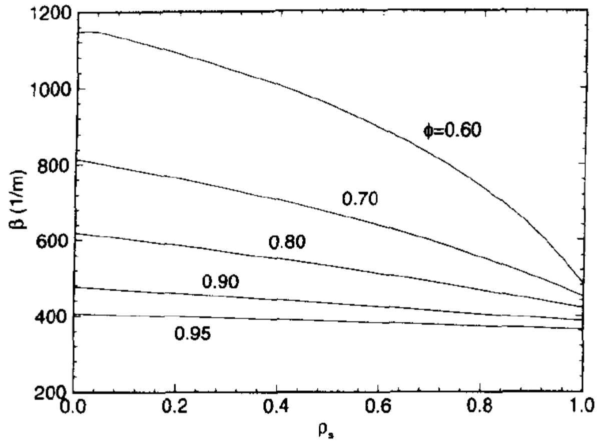
Figures 9 the composed of Henyey-Greenstein phase function.

Doer man and Sacadura [40] proposed a sophisticated models for the extinction coefficient, albedo and phase function of open cell foam on the basis of geometrical optics and diffraction theory, but, unfortunately, they did not compare model predictions with experimental data.

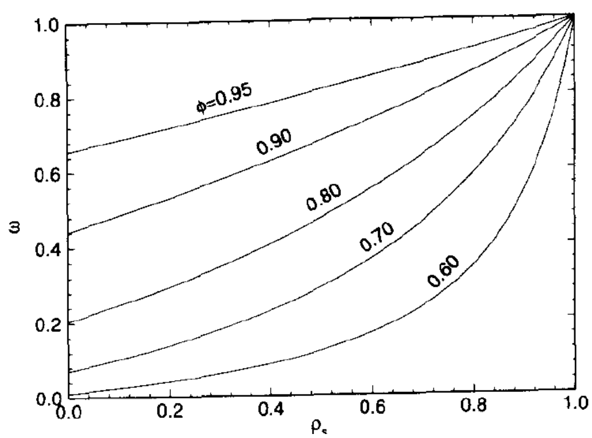
Fu et al. [41] used a unit cell model (Fig. 10) to predict the extinction coefficient β and single scattering albedo ω of reticulated ceramics which the estimated results of Fu et al. [41], i.e., β and ω were illustrated in Fig. 11 and Fig. 12 respectively.



Figures 10 Schematic of unit cell used for the radiative charcteristics model.



Figures 11 Dependence of the extinction coefficient β on the solid reflectivity ρ_s for PPC = 4



Figures 12 Dependence of the single scattering albedo *ω* on the solid reflectivity ρ_s for PPC = 4

Kamiuto [42] derived analytical formulas for the radiative properties of open-cellular porous media by decomposing a Dul'nev's unit cell into two cylindrical struts and one spherical strut juncture as depicted in Fig. 13 [42] and by applying geometrical optics and diffraction theory to these scatterers which were assumed to be randomly oriented in space. Note that there exist three struts in a unit cell but only two are effective in the radiation process because the vertical strut is located in the shadow region of the strut juncture, when thermal radiation is normally incident on the upper surface of the unit cell, and thus does not interact with the incident thermal radiation.

Kamiuto's scaled radiative properties is thus obtained from the equation of transfer where the diffraction scattering phase function is eliminated utilizing Dirac's delta function. The scaled radiative properties are given by

$$\beta = \frac{\pi}{4}\left[\left(\frac{6}{\pi}\right)^{2/3} w^2 + \frac{4w}{\sqrt{\pi}}(1-w)\right] \cdot \left[D_c(1-w)\right]^{-1}, \qquad (20)$$

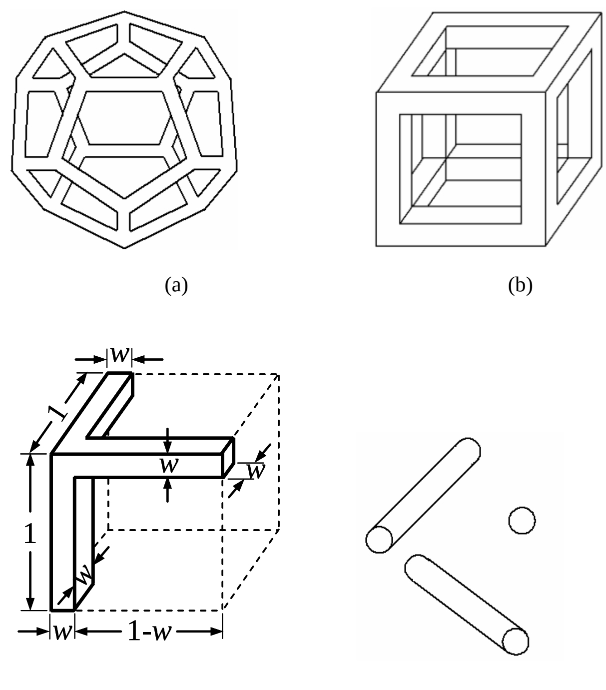
$$w = 0.5 + \cos\left[\frac{1}{3}\cos^{-1}(2\phi - 1) + \frac{4}{3}\pi\right], \qquad (21)$$

$$D_C = 0.254PPI\ , \qquad (22)$$

$$\omega = \rho_H\ , \qquad (23)$$

$$g_d = -4/9\ . \qquad (24)$$

Here, *w* is the dimensionless width of a strut consisting of a cubic unit cell, D_C is the nominal cell diameter defined by 0.254PPI (Pores per inch) in which *PPI* denotes the manufacturing provided mean pores per inch and g_d is the asymmetry factor of the surface-seattering phase function of a diffuse sphere. For the parameter ρ_H, it denotes as the hemispherical reflectivity of the strut and strut junctures.



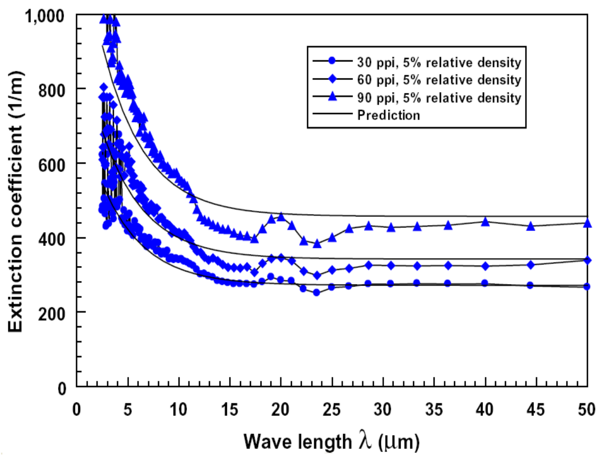
Figures 13 Model systems for open-cellular porous materials:
(a) perspective view (pentagonal dodecahedron cell);
(b) unit-cell model by Dul'nev;
(c) rearranged unit-cell model;
(d) equivalent scatterers derived from the unit-cell

Recently, Zhao et al [4] performed the experimental measurements on radiative transfer in FeCrAlY (A steel based high temperature alloy) foams having high porosity (95%) and different cell sizes, manufactured at low cost from the sintering route. They proposed that the extinction coefficient was function of porosity *ϕ*, cell size d_p and wave length *λ* as obtained by

$$\beta_\lambda = \frac{C}{0.38}\left[1-e^{-(1-\phi)/0.04}\right]\left[\frac{(1-\phi)^{n-0.5}}{d_p}\right] f(\lambda), \qquad (25)$$

$$f(\lambda) = \begin{cases} 1+e^{-2.4\times10^5\left(\lambda-2.5\times10^{-6}\right)}, & \lambda \geq 2.5\times10^{-6} m \\ 2, & \lambda < 2.5\times10^{-6} m \end{cases} \qquad (26)$$

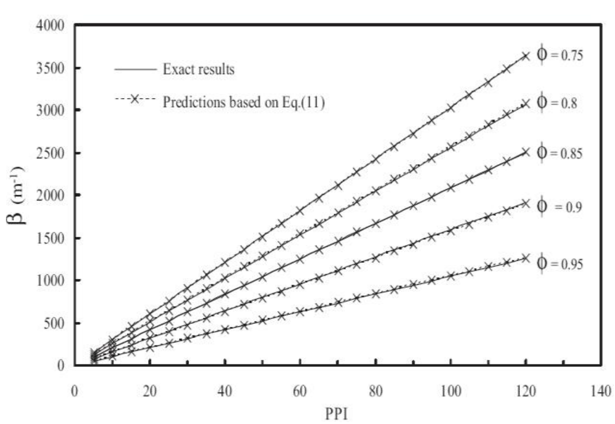
The value of the constant C and n were determined by matching the predicted spectral extinction coefficients from Equation (25) with those measured, as shown in Fig. 14. It is found that n = 1 for all the three samples tested, and C = 0:445, 0.278 and 0.30 for the 30, 60 and 90 ppi foam sample, respectively.



Figures 14 Matching predictions with test data for spectral extinction coefficient.

In addition, one of the authors [43] has proposed the extinction coefficient based on Kamiuto's scaled radiative model (Equation (20)) depicted in Fig. 15. Computations cover the range of PPI from 5 to 120 and porosity from 0.75 to 0.95. The scaled extinction coefficient decreases with an increase in porosity ϕ and increases with *PPI* and is approximately represented by the following expression:

$$\beta = \left(71.508 - 20.62\phi - 45.871\phi^2\right) PPI, \qquad (25)$$



Figures 15 Dependence of the scaled extinction coefficients on the pores per inch (*PPI*) with the porosity (ϕ) as a parameter

5. Conclusions

In the present article review, the major conclusions and recommendations can be summarized as follows:

1) The geometry of the highly porous material, open cellular structure or open-celled foam, can be arranged as *three-dimensional pentagonal dodecahedron* owing to it consists of three-dimensional dodecahedron-like cells with pentagonal or hexagonal open-cell walls.

2) The open cellular porous media is commonly characterized as heterogeneous participating media and thus can be treated as a continuum for purposes to describe the propagation of radiative intensity through the medium.

3) The solution of the radiative heat transfer equation (RTE) is generally solved by two directions: exact and approximated solution method. Both methods may be placed into four different categories, i.e., geometry, temperature field, scattering and radiative properties.

4) The extinction coefficient β, albedo ω and scattering phase function $P(\cos\theta)$ are significant parameters of radiative properties for solving RTE in participating media (Open-cellular porous media).

5) The extinction coefficient β, usually, depends on the porosity (ϕ) and on the morphological structure of the foam, here is the cell or pore diameter.

6) The phase function $P(\cos\theta)$ used for predicting the RTE of open-cellular porous material, favorably, base on Henyey-Greenstein phase function and its application.

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