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Regular article

Pore-level determination of spectral reflection behaviors of high-porosity metal foam sheets

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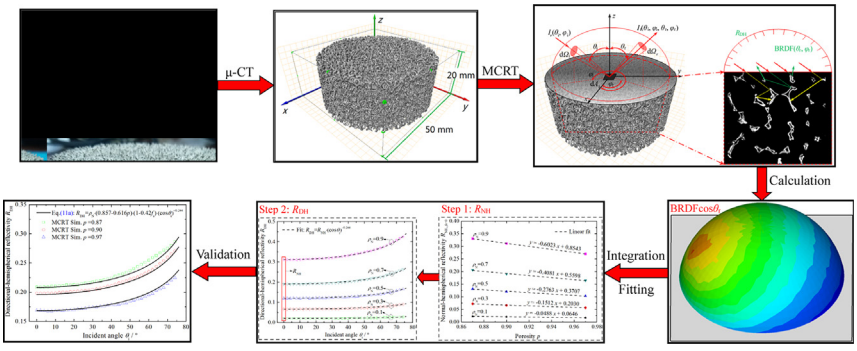
HIGHLIGHTS

- Combination of 3-D tomographied digital geometry and MCRT method.
- Variations in reflectance properties with textural and optical parameters.
- Analytical relations involving hemispherical reflectivity of foam sheets are established.
- Linking hemispherical reflectivity to porosity, complex refractive index, specularity parameter and incident angle.
- Hemispherical reflectivity increases exponentially alongside incident angle cosine.

GRAPHICAL ABSTRACT



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ABSTRACT

Open cell metal foams are currently attracting attention and their radiative behaviors are of primary importance in high temperature applications. The spectral reflection behaviors of high-porosity metal foam sheets, bidirectional reflectance distribution function (BRDF) and directional-hemispherical reflectivity were numerically investigated. A set of realistic nickel foams with porosity from 0.87 to 0.97 and pore density from 10 to 40 pores per inch were tomographied to obtain their 3-D digital cell network. A Monte Carlo ray-tracing method was employed in order to compute the pore-level radiative transfer inside the network within the limit of geometrical optics. The apparent reflection behaviors and their dependency on the textural parameters and strut optical properties were comprehensively computed and analysed. The results show a backward scattering of the reflected energy at the foam sheet surface. Except in the cases of large incident angles, an energy peak is located almost along the incident direction and increases with increasing incident angles. Through an analytical relation established, the directional-hemispherical reflectivity can be related directly to the porosity of the foam sheet and to the complex refractive index of the solid phase as well as the specularity parameter which characterizes the local reflection model. The computations show that a linear decrease in normal-hemispherical reflectivity occurs with increasing porosity. The rate of this decrease is directly proportional to the strut normal reflectivity. In addition, the hemispherical reflectivity increases as a power function of the incident angle cosine.

1. Introduction

Open cell foams possessing large specific surface area, light weight and good flow-mixing capability are currently attracting

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Nomenclature

A	absorptivity of foam sheet
BRDF	bidirectional reflectance distribution function
d_s	strut diameter, mm
D	diameter of foam sheet, mm
I	radiation intensity, W m^{-2} sr^{-1}
L	thickness of foam sheet, mm
f_s	specularity parameter
N	counter for rays
p	porosity
R	reflectivity of foam sheet
S	specific surface area, m^{-1}
T	transmissivity of foam sheet

Greek symbols

α	strut absorptivity
ε	strut emissivity
ζ	random number
θ	zenith angle, °
λ	wavelength, μm
ρ	strut reflectivity
φ	azimuth angle, °
Ω	solid angle, sr
χ	size parameter

Subscripts

DH	directional-hemispherical
i	in
N	normal
NH	normal-hemispherical
NN	normal-normal
r	reflected
λ	spectral

attention as filling materials in various thermal systems [1], such as volumetric solar receivers [2], porous burners [3], thermochemical reactors [4] and heat exchangers [5]. The radiative behavior of foam sheets is of great importance due to the quest for better high-temperature utilization. Typically, the thermal radiative loss of a volumetric solar absorber via solar radiation reflection depends mainly on the effective/apparent reflectivity of the filling foam sheets [6]. Hence one can see that a comprehensive study of the radiative behavior of foam sheets is highly required by existing thermal applications. However, precise investigation of the radiative transfer inside complex structure of realistic foams is rather difficult to perform [7].

The open cell metal foam typically consists of massive solid struts that form a network of interconnected cells in which the radiative intensity can travel by multiple emission-absorption-scattering events [8,9]. The foam sheets thus behave intuitively as semitransparent materials and their volumetric radiative properties (absorption coefficient, scattering coefficient and scattering phase function) attract considerable attention for the modeling of radiative transfer [10,11]. However, these volumetric radiative properties could not be obtained directly through experiments. In practice, the so-called apparent radiative behaviors (such as directional-hemispherical reflectance and transmittance, and directional emittance) are alternatively measured usually by means of an integrating sphere and a controllable turn table [12,13].

Apart from experimental options, the radiative behavior of foams could also be numerically simulated through a pore-level approach that combines 3-D digital foam geometry and rigorous Monte Carlo ray-tracing (MCRT) method. The 3-D digital geometry is usually derived from different shapes of idealized cells (cube [14], dodecahedron [15], tetrakaidecahedron [16], etc.) or from representations that are tomographied from realistic foams [17,18]. Loretz et al. [19] have proved that the use of realistic representations can facilitate a better agreement with the experimental results. However, numerical study of the radiative nature is rather difficult to perform due to the complex random porous structure. To rigorously treat the radiative transfer problem, MCRT method is theoretically required [20]. General hypotheses that facilitate the MCRT simulations include Geometrical Optics Approximation (GOA), opaque surface for metal struts, ignoring diffraction and dependent scattering effects [21,22], etc. So far this pore-level approach has been used for realistic Al foams [23], SiC foams [24,25], NiCrAl foams [26], AlNiP foams [27], and Ni foams [28]. At this point, analytical relations that can link the apparent radiative behavior to the textural parameters and intrinsic optical properties of the foams can be logically extracted from the numerical computations [6,24,29]. Such relations that can easily and accurately compute the apparent radiative behavior are highly required by the foam-based thermal utilizations [11], such as maximizing the solar-to-thermal efficiency of a solar receiver [30,31]. Currently, new possibilities have been developed in this field due to the popularization of the aforementioned pore-level approach. More precise and comprehensive study that involves the apparent radiative behavior of realistic foams can be addressed.

A noteworthy issue is that the apparent radiative behavior of a typical semitransparent material depends on its limited physical size [24]. Obviously, the size-dependent radiative behavior possesses relatively poor applicability. This size-dependence will disappear when the tested sample has ultra-thick size so that it can be regarded as optically thick medium for which the apparent behavior is the same regardless of the thickness [29]. Such ultra-thick foams are usually utilized in most of the thermal applications [2,3,4,5,32,33]. By contrast, the representativeness of the cell network should be strongly suspected if an ultra-thin foam sheet is used to extract the apparent radiative behavior [34,35]. The foam sheet with ultra-thin size is incapable of holding enough unbroken cells to ensure the reproducibility of the results [36]. These facts militate the choice of foam sheets from which their apparent radiative behavior is extracted.

The literature survey indicates that a comprehensive investigation on the apparent radiative behavior of open cell foams is highly required. Meanwhile, there is an immense need for predictive relations that can directly and accurately forecast the apparent radiative behavior. In this work, we attempted to study the apparent reflection behaviors of open cell metal foam sheets in terms of the bidirectional reflectance distribution function (BRDF) and directional-hemispherical reflectivity. Particular attention was focused on establishing analytical relations that can link the directional-hemispherical reflectivity to the textural parameters and intrinsic optical properties of the foam sheets. To achieve these goals, this paper was organized as follows. In Section 2, the image-processing and meshing methods of the digital representations that were tomographied from a set of realistic nickel foams were introduced. The MCRT method that facilitated the modeling of the radiative transfer inside the cell network was then introduced