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Tomography-based radiative transfer analysis of an open-cell foam made of semitransparent alumina ceramics

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ABSTRACT

This study aims to fully investigate the radiative characterization of ceramic foams in terms of local scale (single strut) and macro scale (foam sheet). A radiative transfer model was established in the limit of geometric optics for a porous structure obtained from real alumina ceramic foams by computed tomography technique. The model considers the reflection and refraction at solid-void interface and the volumetric transmission, absorption and scattering process inside semitransparent ceramic solids. It is found that at local scale, neglecting the real hollowness may bring considerable errors to the local radiative behavior of ceramic struts (maximum errors up to 20.4–39.3% for the cases investigated). The cross-sectional thickness of the strut increases from the middle to the extremities, which causes a significant variation of the local radiative behavior. At macro scale, a peak in transmittivity of foam sheet can be observed at the wavelength around 4.4 μm. The scattering albedos obtained from the predictive model indicate that alumina ceramic foams behave strongly scattering within the wavelength 4 μm but very absorbing over 6 μm. The asymmetry factors obtained show a turning point at the wavelength around 1.8 μm, suggesting a transition of the scattered radiation from backward predominance to forward predominance.

1. Introduction

Ceramic foams have been extensively utilized in high-temperature applications due to their light weight, good flow-mixing capability, and ability to cover large surface area. They are composed of interconnected solid struts and accessible void spaces, thus being typical two-phase media. As reviewed by Viskanta and Menguc [1] and Baillis and Sacadura [2], precise analysis of radiative transfer in such porous media is of fundamental importance to many thermal applications, such as volumetric solar receivers [3], porous burners [4], thermochemical reactors [5] and heat exchangers [6]. From the perspective of volumetric radiation, the ceramic foams are commonly treated as semitransparent absorbing-scattering media at macro scale [7]. Furthermore at local scale, the ceramic struts themselves, as basic component element of ceramic foams, are in reality also semitransparent absorbing-scattering media for certain wavebands. The semitransparent nature at macro scale and local scale jointly makes the radiative transfer analysis of ceramic foams relatively complex. Related projects are attracting considerable attention. Randrianalisoa and Baillis [8] have also called attention to this frontier field.

Ceramic foams behave like semitransparent media in which the radiative intensity can travel inside the solid phase and/or pass through the void phase by multiple emission-absorption-scattering events [9]. According to modelling scale, the numerical methods for radiative transfer analysis of porous materials can be divided into two classes: continuous-scale approach (CSA) and discrete-scale approach (DSA) [10,11]. The CSA assimilates the porous material to a continuous semitransparent medium with equivalent volumetric radiative properties (such as extinction coefficient, scattering albedo and scattering phase function) [12]. Based on media radiation transfer theory [13], the volumetric propagation phenomena, emission, absorption and scattering are generally taken into account. Cunsolo et al. [9] and Baillis et al. [14] have reviewed the key elements of the CSA. By contrast, the DSA considers the exact distribution of solid and void phases in the porous materials. It commonly combines complex 3D foam geometry and radiative transfer solving methods such as Monte Carlo ray-tracing (MCRT) procedure [15]. The foam geometry is usually derived from idealized geometric models (such as cube structure [16], Lord Kelvin structure [17,18], Weaire-Phelan structure [19], Voronoi structure [20,21], and modified structures from these primary ones [22,23]) or from real foams through computed tomography (CT) technique [24,25]. Compared to the idealized geometric models, 3D tomographic geometry enables representing more truly the real structure morphology, such as concave/convex struts [26,27], partially

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Nomenclature

A_{D}	absorptivity of foam sheet
$\hat{A}_{\mathrm{D}}$	local absorptivity of ceramic strut
D_{foam}	diameter of foam sheet, mm
d_{c}	mean cell diameter of foam, mm
d_{cs}	cross-sectional diameter of strut, mm
g	asymmetry factor of foam
I	radiation intensity, W m^{-2} sr^{-1}
L_{foam}	height of foam sheet, mm
L_{slice}	height of ceramic slice, mm
l_{as}	available strut length, mm
l_{ch}	edge length of hollowness cross-section, mm
l_{cs}	edge length of strut cross-section, mm
l_{free}	extinction free path, mm
l_{β}	transfer distance of a ray inside solids, mm
N	number of rays
n_{solid}	refractive index of solid phase
n_{void}	refractive index of void phase
PPI	pores per inch
p	foam porosity
R_{DH}	reflectivity of foam sheet
$\hat{R}_{\mathrm{DH}}$	local reflectivity of ceramic strut
$\vec{r}$	position vector, mm
S_{cc}	cross-sectional area of ceramic solids, mm^2
S_{ch}	cross-sectional area of hollowness, mm^2
S_{cs}	total cross-sectional area of strut, mm^2
$\vec{s}$	propagation direction vector
$\vec{s}'$	incoming direction vector
$\vec{s}_{\mathrm{in}}$	incident direction vector to a strut
$\vec{s}_{\mathrm{out}}$	outward direction vector from a strut
T_{DH}	transmittivity of foam sheet
$\hat{T}_{\mathrm{DH}}$	local transmittivity of ceramic strut
W	scattering angle distribution parameter

Greek symbols

β	extinction coefficient of foam, m^{-1}
β^*	weighted extinction coefficient of foam, m^{-1}
β_{solid}	extinction coefficient of solid phase, m^{-1}
θ_{emi}	local emitting zenith angle at strut surface, °
θ_{in}	local incident zenith angle at strut surface, °
$\theta_{\mathrm{in\_foam}}$	incident zenith angle at foam surface, °
θ_{r}	local reflected zenith angle at strut surface, °
$\theta_{\mathrm{r\_foam}}$	reflected zenith angle at foam surface, °
θ_{sca}	scattering angle, °
θ_{t}	local refracted zenith angle at strut surface, °
κ_{solid}	absorption coefficient of solid phase, m^{-1}
λ	wavelength, μm
ξ	dimensionless position of strut
ρ	local reflectivity at solid-void interface
σ_{s}	scattering coefficient of foam, m^{-1}
σ_{s}^*	weighted scattering coefficient of foam, m^{-1}
$\sigma_{\mathrm{s\_solid}}$	scattering coefficient of solid phase, m^{-1}
ζ	random number
Φ	scattering phase function of solid phase, sr^{-1}
$\varphi_{\mathrm{in\_foam}}$	incident azimuth angle at foam surface, °
$\varphi_{\mathrm{r\_foam}}$	reflected azimuth angle at foam surface, °
Ω	solid angle, sr
ω	scattering albedo of foam
ω^*	weighted scattering albedo of foam
ω_{solid}	scattering albedo of solid phase

Subscripts

a	absorbed
DH	directional-hemispherical
D	directional
emi	emitting
ext	extiction
r	reflected
sca	scattering
t	transmitted
λ	spectral

Acronyms

BRDF	Bidirectional Reflectance Distribution Function
CSA	continuous-scale approach
CT	computed tomography
DSA	discrete-scale approach
GOA	geometric optics approximation
IAD	Inverse Adding-Doubling
MCRT	Monte Carlo ray-tracing
REV	Representative Elementary Volume
RTE	Radiative Transfer Equation
SEM	scanning electron microscope

hollow struts [28,29], and struts with enlarged cross-section between their center and their extremities [8,27,30]. To rigorously solve the radiative transfer in real foams, the MCRT method is theoretically required [15]. For the DSA in two- and multi-phase media, one can refer to the comprehensive studies by Randrianalisoa and Baillis [8], Loretz et al. [24], and Cunsolo et al. [27] as well as the fundamentally theoretical modelling by Lipinski et al. [31–33], Coquard et al. [34] and Gusarov et al. [35–38]. To conclude, the DSA can predict radiative quantities of porous materials more accurately than the CSA [39]. The studies on the basis of tomographic foam geometry enable obtaining relatively reliable results and facilitating a better agreement with experimental measurements [40].

Commonly, the radiative behavior (such as transmittivity, reflectivity, and absorptivity [41]) and equivalent volumetric radiative properties (such as extinction coefficient, scattering albedo and scattering phase function [42]) are used to describe the radiative characterization of a porous medium. In practice, the radiative behavior can be directly measured through experimental techniques with the help of, for example, an integrating sphere and a controllable turn table [43,44]. Therefore, the radiative behavior is also known as measurable property. These radiative quantities can also be obtained through numerical experiments on discrete-scale simulation i.e. the DSA. From the radiative behavior obtained, the equivalent volumetric radiative properties can be retrieved [45]. Coquard and Baillis [46,47] developed a numerical approach to directly obtain the equivalent volumetric radiative properties from a mean free path and scattering distribution calculation. Then Randrianalisoa and Baillis [48,49] and Coquard et al. [34,50,51] extended this numerical approach into several real porous media. The approach works well for packed particle beds, closed-cell polymeric foams, and open-cell metal foams, etc. Inspired by their studies, this numerical approach will be further applied in ceramic foams to calculate their equivalent volumetric radiative properties.

A particular attention is paid to the constructional element of the open-cell ceramic foams: the solid struts also called skeletons or ligaments. Unlike the silicon carbon ceramics [52], alumina ceramics are in reality semitransparent for certain wavebands [53]. This means the ceramic struts themselves are absorbing-scattering media for radiation propagation due to the composition of a high density of micronic