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# Pore-level numerical analysis of the infrared surface temperature of metallic foam

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ABSTRACT

Open-cell metallic foams are increasingly used in various thermal systems. The temperature distributions are significant for the comprehensive understanding of these foam-based engineering applications. This study aims to numerically investigate the modeling of the infrared surface temperature (IRST) of open-cell metallic foam measured by an infrared camera placed above the sample. Two typical approaches based on Backward Monte Carlo simulation are developed to estimate the IRSTs: the first one, discrete-scale approach (DSA), uses a realistic discrete representation of the foam structure obtained from a computed tomography reconstruction while the second one, continuous-scale approach (CSA), assumes that the foam sample behaves like a continuous homogeneous semi-transparent medium. The radiative properties employed in CSA are directly determined by a ray-tracing process inside the discrete foam representation. The IRSTs for different material properties (material emissivity, specularity parameter) are computed by the two approaches. The results show that local IRSTs can vary according to the local compositions of the foam surface (void and solid). The temperature difference between void and solid areas is gradually attenuated with increasing material emissivity. In addition, the annular void space near to the foam surface behaves like a black cavity for thermal radiation, which is ensued by copious neighboring skeletons. For most of the cases studied, the mean IRSTs computed by the DSA and CSA are close to each other, except when the material emissivity is highly weakened and the sample temperature is extremely high.

## 1. Introduction

Open-cell foam materials have been extensively utilized in thermal engineering systems due to their light weight, good flow-mixing capability and ability to cover large surface area [1]. These materials have been applied in volumetric solar receivers [2], porous burners [3], chemical reactors [4], and heat exchangers [5]. The temperature distribution plays a crucial role in characterizing the thermal performance of these systems [6]. Among various techniques used in temperature measurements, infrared cameras have been widely used to measure the surface temperatures of foam materials in a non-invasive manner with almost no-time-delay. However, due to the complexity of porous structures, a better understanding of the infrared surface temperature (IRST) of foam materials is required especially at pore-level.

In the existing experimental studies, researchers have widely used the infrared cameras to measure the surface temperatures of foam materials. Hwang et al. [7] measured the solid-phase temperature distributions on the exit plane of aluminum foams using an infrared camera. Fend et al. [8] recorded the variations of temperature distributions during a cooling process by monitoring the front surface of several porous materials with an infrared camera. Additionally, Albanakis et al. [9] employed an infrared camera to estimate the temperature fields at air inlet of a volumetric solar receiver filled with metallic foams. Moreover, Michailidis et al. [10] used the measured temperature fields to model the discrete-scale flow and conducted a thermal simulation to a representation from computed tomography (CT) technique. Wu et al. [11–12] utilized an infrared camera to measure the inlet surface temperature of a solar porous absorber using a reflector. Similarly, Keramiotis et al. [13] used an infrared camera to obtain the solid phase temperature distribution of a two-layer porous burner. Furthermore, Mey-Cloutier et al. [14] developed a test bench to investigate the solar-to-thermal efficiency of reticulate porous ceramics with open pores. In their study, the map of blackbody equivalent temperature of the porous ceramics was recorded by infrared camera. Based on existing literature, measured infrared temperature fields play significant role in: evaluating and perfecting the performance of foam-based thermal systems [7–9,14], validating corresponding numerical analyses [11–12] and setting boundary conditions in associated thermal simulations [10]. It is worth to note that, non-

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**Nomenclature**

| | |
|---|---|
| $A$ | integration over enclosure surface area, m$^2$ |
| $A_0$ | visible area of camera, m$^2$ |
| $A_{lens}$ | lens area of camera, m$^2$ |
| $A_s$ | specific area, m$^2$/g |
| $d_s$ | mean skeleton diameter, µm |
| $D$ | diameter of foam representation, mm |
| $\vec{E}$ | node of surface element |
| $F_{\Delta\lambda}$ | blackbody band radiation function |
| $G$ | radiative flux received by camera, W m$^{-2}$ |
| $H$ | height of foam representation, mm |
| $I$ | radiation intensity, W m$^{-2}$ sr$^{-1}$ |
| $l$ | mean free path, m |
| $l_0$ | distance between foam and camera, m |
| $l_z$ | total length of zig-zag path, m |
| $L$ | counter for traveled distance |
| $\vec{n}$ | normal vector at solid surface |
| $N$ | counter for rays |
| $N_{ele}$ | number of surface elements |
| $P_s$ | specularity parameter in range [0, 1] |
| $P(x, y)$ | pixel |
| $\vec{r}$ | position vector |
| $R_\zeta$ | random number in the range [0, 1] |
| $\vec{s}$ | direction vector |
| $S$ | local radiative source, W m$^{-3}$ sr$^{-1}$ |
| $T$ | temperature, K |
| $T_{IR}$ | infrared temperature, K |
| $V$ | integration over enclosure volume, m$^3$ |
| $V_{IR}$ | response voltage of infrared camera, V |
| $W$ | distribution parameter of scattering angle |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | absorptivity |
| $\beta$ | extinction coefficient, m$^{-1}$ |
| $\delta$ | Dirac-delta function |
| $\Delta\lambda$ | working wavelengths of camera, µm |
| $\varepsilon$ | emissivity |
| $\theta$ | scattering angle |
| $\theta_i$ | starting angle, rad |
| $\kappa_a$ | absorption coefficient, m$^{-1}$ |
| $\lambda$ | wavelength, µm |
| $\rho$ | reflectivity |
| $\sigma$ | Stefan-Boltzmann constant |
| $\sigma_s$ | scattering coefficient, m$^{-1}$ |
| $\phi$ | porosity |
| $\Phi$ | scattering phase function |
| $\omega$ | scattering albedo |
| $\Omega$ | solid angle, sr |
| $\Re_\lambda$ | spectral response ability of camera, V W$^{-1}$ |

*Subscripts*

| | |
|---|---|
| $0$ | foam material |
| $a$ | apparent |
| $abs$ | absorption |
| $b$ | background |
| $diff$ | diffuse |
| $emi$ | emitted |
| $ext$ | extinction |
| $i$ | current location |
| $n$ | ray identifier |
| $rec$ | received |
| $s$ | surroundings |
| $sca$ | scattering |
| $spec$ | specular |
| $w$ | wall |
| $\gamma$ | transmission |
| $\varepsilon$ | emission |
| $\lambda$ | spectral |
| $\rho$ | reflection |

homogenous surface temperature distributions at pore-level was observed in some of those experimental studies [11,13–14]. Nevertheless, the pore-level characteristics of IRSTs associated with real porous structures have not been fully considered and analyzed.

Analysis of radiative transfer in foam materials is fundamental in understanding IRSTs. According to the geometric modeling of foam sample, the numerical methods for radiative transfer in foam materials can be classified as continuous-scale approach (CSA) and discrete-scale approach (DSA) [15]. The structure of highly porous materials is not sufficiently dense to be considered as opaque to thermal radiation [16]. Therefore, the previous studies have considered foam materials as continuous homogeneous semi-transparent media based on radiative properties associated with porosity and particle/pore size [17–18]. However, this continuous treatment of foam materials is limited by the validity of these property correlations, and even leads to significant errors [19]. To overcome the limitations relative to the use of correlations, a computation method of radiative properties has been proposed based on a discrete-scale ray-tracing process inside the real porous structure using the 3-D representation from a CT technique. This computation method was initially proposed by Coquard and Baillis [20] and then extended by Randrianalisoa and Baillis [21] and Coquard et al. [19,22–23]. Evidently, the radiative properties computed from the real porous structure can better model the radiative transfer in foam materials. This "combined method" will inspire this current study. Beside the CSA, DSA is another typical method that can be used to investigate the radiative transfer in foam materials. It fully implements the radiative transfer simulations in the structures of different shapes of ideal cells (cube, dodecahedron, tetrakaidecahedron etc.) [24–26] or the representations from CT technique [27–28]. Apparently, studies based on CT technique have proven in providing a wholistic understanding of the real structure of foams [29]. The discrete-scale radiative transfer simulations are commonly subjected to several assumptions such as geometrical optics approximation (GOA) [30], opaque surface for metallic skeletons [31] and absence of diffraction and dependent scattering effects [32]. Based on those assumptions, a better understanding of the effects of morphological features and material properties on radiative transfer in foam materials can be achieved [33]. Therefore, these existing researches will encourage this current study on the local IRSTs of foam materials associated with its local composition.

The literature survey indicates that the non-homogenous surface temperature distributions of porous or foam materials have been observed at pore-level in experimental studies [11,13–14]. However, the pore-level distribution characteristics of IRST have not been comprehensively studied, especially for the real porous structures. The previous studies that investigated this temperature distribution based on the real porous structures are relatively scarce. In this study, the characteristics of the IRST of an open-cell metallic foam are numerically investigated at both discrete and continuous-scales. The geometry representation of the metal-