Towards the development of simple methods for determining normal absorptances of open-cell foams based on opaque materials

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Abstract. The knowledge of the normal spectral absorptances of open-cell foams used as volumetric solar receivers is required to finely compute their thermal efficiencies. For this purpose, absorptances of a set of virtual open-cell foams of varying porosities, beforehand generated by using a numerical generator, are computed thanks to a ray tracing code. This work details the contribution of the intrinsic optical properties of the solid phase to the normal spectral absorptance of open-cell foams, through the statistical analysis of both the path and the events undergone by a ray, which is permitted by the ray tracing code. This study allows us to propose a robust and linear relationship that links the normal spectral absorptance to the porosity and the intrinsic optical properties of the solid phase, which is considered as optically thick.

1. Introduction
The production of electric power from solar thermal energy, specifically technologies based on concentrated solar power, is nowadays growing at a fast pace. The optimization of heat conversion that occurs within the receiver, on which solar radiation is concentrated, is crucial in order to obtain higher efficiencies. The use of volumetric porous absorbers, based on open-cell silicon carbide foams (SiC), permits to heat the outside air that is pumped directly through the porous media at high temperatures (1000 - 1400 K). In particular, the accurate determination of the radiative exchanges within SiC open-cell foams requires the finding of the links between their textural features and their radiative properties. Several computational approaches, allowing the characterization of the both the homogenized absorption and scattering coefficients as the scattering phase function, were developed to fulfill this objective and were recently summarized by Baillis et *al.* [1]. The present paper focuses on the prediction of the normal spectral absorptance, A, which is especially needed to predict the temperature profiles that occurs within insolated foams [2]. Contrarily to the previous homogenized radiative properties, the links between foam's textural parameters and its absorptance are less known [3]. Thus, a ray tracing code and a numerical foam generator [4, 5], have been combined.

By using these numerical tools, a set of foams with varying porosity was generated to study the impact of porosity on the absorptance. Akolkar and Petrasch [3], made a study with fixed solid interface reflectivity values and for volumes smaller than representative elementary volume (REV) for A. The current work goes further by attempting to establish a robust and simple linear relationship that directly links A to the porosity of the foam, p, and to $\tilde{n}$ (*i.e.* the complex index of refraction $\tilde{n} = n + ik$, with n and k being respectively the refractive and absorptive index), within volumes higher than REV.

2. Set of foams with varying porosity

The foam generator allows to generate open-cell foams whose textural features (porosity, specific surface, pore size distribution mean cell connectivity) are close to those measured on the real SiC foam of interest. The measurement of those textural features was realized thanks to the free software iMorph. A set of four cubic foam samples, whose PPI (number of Pore Per Inch) value are equal to 23 and porosities values are equal to 0.3, 0.5, 0.7 and 0.9, was generated.

3. Ray tracing procedure and ray transport statistical analysis

The ray tracing procedure allows the computation of the normal hemispherical reflectance, R_{NH}, and transmittance, T_{NH}. The comparizon between the thermal radiation wavelength and the pores and struts sizes allows the use of geometrical optics approximation. A large number of rays $N_{rays} = 10^6$, whose directions are collimated to the normal of the foam sample, are launched within a circular spot. Each ray is independently tracked through the 3D reconstruction as follows: void phase is considered as non-participating media and, at each local interaction with the solid phase, a local reflectivity is computed via a specular model according to Fresnel's law. This model needs the knowledge of $\tilde{n}$ of the solid phase constituting the struts. In this work, we will use a set of couple (n, k) which can guarantee a modulation of the local reflectivity. With these couples, we can cover the optical properties of SiC and other opaque material for the considered thicknesses of the struts. Once R_{NH} and T_{NH} are computed, normal spectral absorptance A can be obtained since $A = 1 - R_{NH} - T_{NH}$. A thorough statistical analysis of ray transport, allowing the determination of the total number of ray impacts on the solid phase, and the related mean local reflectivity values, is made for each ray path.

4. Results

A computations were realized on the same cubic foam numerical sample of varying porosities, with a wide range of arbitrary n and k values ($n \in [1.5 - 2.5]$ and $k \in [0.5 - 8]$). The volumes of the samples were larger than the REV determined for A, implying that $T_{NH} = 0$. For each computation, the mean local reflectivity ρ_m was computed. ρ_m is defined here by the average, over each ray path within an entire ray tracing computation, of the successive local reflectivity values that are given by the Fresnel's law. Along a single ray path on which it undergo N_{imp} impacts, the mean local reflectivity related to this ray path, $\rho_{m,path}$, is given by:

$$\rho_{m,path} = \frac{1}{N_{imp}} \sum_{1}^{N_{imp}} \rho_i \qquad (1)$$

with ρ_i being the computed reflectivity at the ith impact. ρ_m does not take into account energy loss due to the multiple reflections of a ray and must be considered here as a statistical mean local reflectivity related to the distribution of the orientations of the facets encountered along the paths of a ray tracing computation.

Fig. 1 shows A as function of p, n and k for several arbitrary n and k values. A grows linearly with porosity, and each slope (denoted here S) related to a specific n and k couple, and so on, to a particular ρ_m value, were computed. For n and k values that give high values of ρ_m, the lower
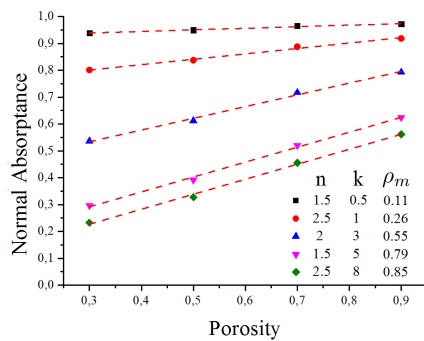
Figure 1. Normal absorptance as function of the porosity for abitrary n and k values.
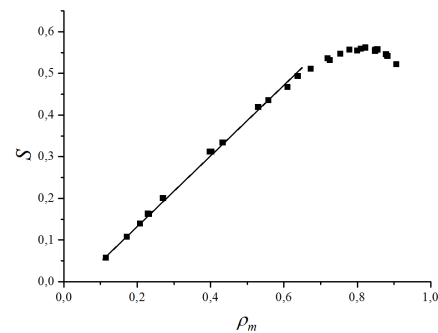
Figure 2. Slopes S (of A as function of p) as function of the mean local reflectivity ρ_m.

is A, and the stronger is the influence of p. The values of the slopes S are plotted as function of the ρ_m corresponding to the same A computations on Fig. 2. It is shown that S depends linearly of ρ_m values on a wide range of ρ_m values. As ρ_m is a function of n, k and the incident angle distribution, this feature allows to define S values also as a function of the intrinsic optical properties of the solid phase constituting the foam. For highly reflective materials ($\rho_m > 0.6$) the value of S decreases. This results permits to show that (for $\rho_m < 0.6$),

$$A = \frac{3}{4} \times \rho_m \times p + A_{strut}, \tag{2}$$

where ρ_m depends on n, k and on the angle distribution of the facets, and with A_{strut}, the absorptance of a strut. Special attentions must be paid now to take into account the influence of the multiple reflections when computing ρ_m values.

5. Conclusion
A linear relationship that links A to porosity and intrinsic optical properties of the solid phase constituting the struts was found in this work, for volumes higher than REV. It is shown that in this case, A can be simply deduced from measurement performed on a dense slab with similar chemical composition. This result relies on a thorough statistical analysis of the transport of rays which permits us to go further in the prediction of radiative properties of foams. However, the influence of the orientation distribution of the facets constituting the 3D reconstruction on this results must be quantified.

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