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Scattering properties of solid rough surface of nickel skeleton

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ABSTRACT

The micromorphology of solid skeleton makes a significant influence on the radiative transfer in metal foams. The modeling of complex morphology of rough surface and the prediction of bidirectional reflectance distribution function (BRDF) are the key issues for the radiative calculation of metal foam. In this work, a modeling method of analyzing and simplifying the complex rough surface using the SEM figures of metal foam's skeleton is introduced. This method is also used to predict the scattering properties of nickel foam's skeleton. Meanwhile, the hemispherical structures are used to replace the real convex structures on skeleton's surface. These hemispherical convex are located on the surface randomly, and the radius of adapted hemispherical convex respect the distribution function extracted from SEM statistic data. Furthermore, the FDTD method is adapted to predict the reflectivity and BRDF of simplified rough surfaces models. The results show that the reflectivity is affected by the size parameter obviously, while it's changed slightly by different incident angles. As for the BRDF of skeleton's rough surfaces, the value of main peaks increase obviously and the scopes of main peaks decrease with the size parameter increasing. The sub-peaks locate differently surrounding the main peaks, and then fuse gradually with the increasing size parameter. The sub-peaks vanish completely at the size parameter up to 6. When it comes to the hemispherical space, the reflection vary from anisotropic reflection to isotropic reflection except the mirror direction. At a larger size parameter, the reflection of rough surfaces can be simplified as the combination of mirror reflection and diffuse reflection. While at a small size parameter, the BRDF of rough surface need to be calculated accurately to reduce the error in the prediction of radiative transfer.

1. Introduction

Metal foam is an attracting wide focus on thermal applications, such as high-temperature exchangers [1,2], solar receivers [3,4] and so on. Radiative transfer is vital for the heat and mass transfer of metal foam. The structure inside metal foam has great influence on the radiative transfer. There are lots of excellent works for the research of the radiative transfer of metal foam. Rousseau [5] made the numerical prediction of the radiative behavior of metallic foams with the Monte Carlo Ray Tracing (MCRT) program. Li made the prediction of the spectral reflection behaviors of high-porosity metal foam sheets, bidirectional reflectance distribution function and directional-hemispherical reflectivity with the Monte Carlo ray tracing method [6], and a predictive relationship was established that links the homogenized apparent emissivity to the open porosity and the intrinsic emissivity of solid struts [7]. The modeling of the infrared surface temperature of open-cell metallic foam with the discrete-scale approach (DSA) and continuous-scale approach based on Backward Monte Carlo simulation was investigated by Li and Xia [8]. However, in most researches about the radiative transfer in metal foam, the radiative properties of skeleton's surfaces are usually from assumptions and empirical formulas. Actually, due to the complex morphology on the rough surface of skeleton, the radiative properties of metal foam's skeleton are usually complex and cannot be described with uniform functions.

For getting a better prediction of radiative transfer in metal foam, the radiative properties of skeleton's rough surface need to be calculated accurately. The extreme complex morphology of skeleton's surface produces large error between the actual anisotropic reflection and the regular expression of functions, and the complex morphology of skeleton's surface makes the radiative transfer in metal foam hard to predict. So the radiative properties of rough surface are the key issues for further study. For predicting the radiative behavior of rough surfaces, plenty of outstanding works have been fulfilled. Parviainen [9] studied the light scattering from self-affine homogeneous isotropic random rough surfaces by using the ray-optics. Zhang [10] applied the updated conventional geometrical optics ray-tracing method by considering the effect of the interference to study the radiative properties of a one-dimensional random rough surface and compared with the results by applied the FDTD method. Feng [11] measured the polarized BRDF of surfaces with an experiment and verified a hybrid model of polarized

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BRDF for rough surfaces. Wang [12] established a five-parameter BRDF model of rough surface and made an experimental verification within infrared band. Kang [13] modeled the micro-scaled rough surface respecting the Gaussian distribution and predicted the radiative properties with the FDTD method. Qi [14] analyzed the BRDF of fractal rough surface by applying the numerical calculation. The spectral reflectivity of a periodic surface in the thermal radiation wavelength range was predicted by Mendeleyev [15] and the influence of orientation of rough grooves were discussed. However, almost all the present works are focus on the rough surfaces of bulk material. What's more, the surfaces are usually modeled by mathematical expression, such as the Gaussian surfaces and the fractal surfaces. However, there are obvious differences between the bulk material and the skeleton of metal foam due to the various fabrication process. Few studies consider the real morphology of skeleton's surface, which can't be described with simple mathematical formulas. The surface of skeletons are usually complex since the fabricating technique [16–18] and the real morphology need to be analyzed by applying advanced technique. Coquard [19] considered the influence of skeleton's rough surface on the radiative properties of metal foam and predicted the radiative transfer with geometric optics since the characteristic sizes of the cells are almost always much greater than infrared radiation wavelengths, and the sizes of structures on the skeleton surface were still in the range of geometric optics. However, the application of geometric optics is limited by the size of structures. The Maxwell equations and other electromagnetic theories [20] are needed to study the radiative properties of skeleton rough surfaces when the characteristic sizes of structure are similar to the wavelength. The prediction of radiative properties of skeleton's surfaces inside metal foam hasn't attracted further attention.

For getting the accurate radiative properties of micro-scaled structures, the numerical techniques should be adapted. The finite-difference time-domain (FDTD) method [21] is one of widely used methods for the radiative transfer of micro-scaled structures. Qiu [22] made an analysis of infrared radiative properties of one dimensional periodic aluminum surfaces with various micro-scale triangular gratings using the FDTD method. Chen [23] applied a computational model based on the finite-difference time-domain method and the Wiener Chaos Expansion (WCE) method to calculate the near-field radiative heat transfer between two plates with Gaussian type rough surfaces. Wang [24] studied the absorption characteristics of plasmonic metamaterials with an array of nanoshells with the FDTD method. The reliability of the FDTD method has been proved by plenty of works.

In this work, by applying the SEM technique, a method is introduced for building the simplified model of rough surface of solid skeleton. And the skeleton's surface of Ni foam is analyzed by applying the method. The FDTD method is adapted to get the reflectivity and BRDF of skeleton's surface with various parameters. The results are compared and discussed. This work can be benefit to the analysis of radiative properties for the radiative transfer in whole metal foam. The model adapted is introduced in Section 2. In Section 3, the numerical method and calculation condition are presented. The results and analyses are discussed in Section 4 and the conclusions are summarized in the following section.

2. Model

For the radiative transfer in metal foam, the prediction for radiative properties of skeleton's surface is a significant issue. The surfaces of skeletons are usually complex in morphology, which affect the radiative parameters of the whole foam. The structures on the skeleton's surface are usually wavelength-scaled as shown in Fig. 1.

Fig. 1 is the scanning picture of skeleton of electrolytic Ni foam with the SEM technique. The morphology of metal foam's skeleton is complex and difficult in constructing the real three-dimensional structure. Therefore, simplified rough surfaces are needed and the methods of simplifying the surfaces deserve further researches. In this work, a method is introduced for modeling the simplified surfaces, and then the method is adapted to model the skeleton's surfaces of electrolytic Ni foam. The operations of the introduced method are shown as following.

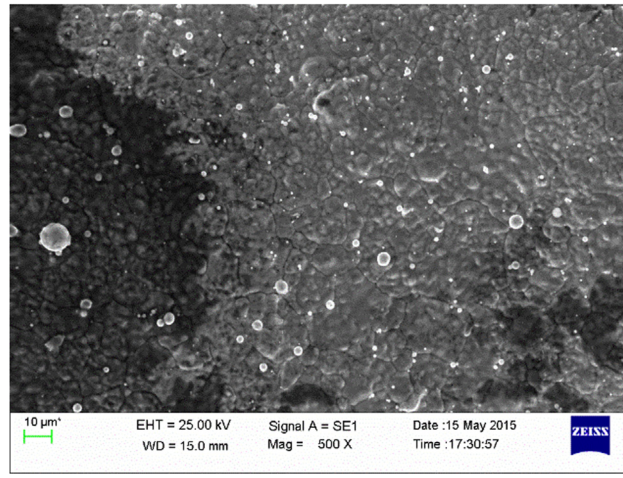

Fig. 1. The surface of electrolytic Ni foam's skeleton from SEM scanning.

(a) Firstly, the figures of skeleton's surface such as Fig. 1 are got by applying the SEM technique. The characteristics of the structures on the skeleton surfaces are observed and summarized. The regular structures with common shapes are adapted to simplify the micro-scale complex structures on the rough surfaces. The adapted simplified structures are approximate to the micro-scaled structures on the surfaces.
(b) Secondly, the technique for analyzing the scanning pictures is used for getting the statistic data of surface's micro-scaled structures. In this process, the sizes, amounts and other characteristics are counted and analyzed. The statistic data is used to model the micro-scaled structures, and the modeling of simplified rough surfaces is carried out later.
(c) Furthermore, the simplified surfaces are modeled with the chosen regular structures. The sizes and locations of adapted simplified structures are from the statistic data above. The modeled rough surfaces are approximate to the scanning pictures of skeleton and own the statistical characteristics.
(d) At last, the radiative properties of modeled rough surfaces can be predicted after calculating. The predicted radiative parameters are compared and analyzed. The predicted properties are the basis of further research about the radiative transfer of metal foam.

For better understanding of the introduced method and further researches, the rough surfaces of electrolytic metal Ni foam's skeleton are modeled by applying the method above. The details and results are shown in following sections in this work.

After observing and analyzing Fig. 1, the skeleton's surface is rough and made up of abundant random convex structures. The random micro-scaled structures are similar to part of sphere with different radius. For simulating the real surfaces, the incomplete spheres are adapted to instead the convex structures on the surface. The adapted approximate hemispherical structure is shown in Fig. 2.

The hemispherical structure is characterized by two features, including the bottom radius r and the height h as shown in Fig. 3.

For better characterizing the surface's morphology, the technique for analysis of scanning figure is used to analyze the scanning picture shown in Fig. 1, the bottom radius of different convex structures and the distances between adjacent convex structures are measured and counted. For 500 convex structures are measured in this work, the statistic data of radius are shown as Fig. 4 followed.

In Fig. 4, r is the bottom radius of convex structure, and N is the