THERMAL CONDUCTIVITY OF POROUS CARBON FOAM

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Introduction

Mesophase pitch-derived open-cell carbon foams with high thermal conductivities have been developed at Oak Ridge National Laboratory [1]. This novel pitch-derived carbon foam is completely different from the vitreous glassy carbon foam produced commercially. The carbon foam cell appears to resemble the shape of a spherical structure consisting of an interconnecting network of carbon struts and strut junctures.

The present work focuses on the interaction between the overall thermal conductivity of carbon foam and foam porosity, morphology, and temperature.

Model

In order to include the most dominant features that have first-order effects on the overall thermal conductivity of carbon foam and to yield a simple geometric model at the same time, the present model considers the carbon foam as a collection of randomly oriented and distributed cubic cells. Each cubical cell is made up of twelve struts with square cross-sectional area and eight cubic strut junctures, see Figure 1.

In view of the analogy between thermal and electric resistors, the heat conduction in each cell is simulated by using series and parallel combinations of resistors. The carbon struts are assumed to be anisotropic since they are made up of graphite layers that are highly anisotropic. Namely, the longitudinal thermal conductivity of carbon strut, k_{sl}, the transverse thermal conductivity of carbon strut, k_{st}, and that of the strut juncture, k_{sj}, where fold-sharpening and crystal misalignment are observed, are different from each other. The heat flow, q, is assumed to be in the x-direction while the four boundary surfaces of the cell that are perpendicular to the y-z plane are assumed to be adiabatic (Figure 1). The unidirectional effective thermal conductivity, k^*, of the cell is given by

$$k^* = k_g(1-t)^2 + \frac{k_{sl}k_{sj}t^2}{k_{sl}t + k_{sj}(1-t)} + \frac{2k_{st}k_g t(1-t)}{k_g t + k_{st}(1-t)} \qquad (1)$$

where t (= Δ / L) is the normalized thickness and can be expressed in terms of foam porosity ϕ by

$$t = \frac{1}{2} + \cos\left(\frac{1}{3}\cos^{-1}(2\phi - 1) + \frac{4}{3}\pi\right) \qquad (2)$$

When $k_{sl} = k_{st} = k_{sj}$, this model reduces to Dul'nev's model [2], which has been verified by comparison with experimental results of reticulated porous foams [3]. In view of symmetry, the results obtained above can be extended to the case where the heat flow is in the y or z direction [4]. With the aid of coordinate transformation, the overall effective thermal conductivity of carbon foam consisting of randomly distributed cubical cells is given by

$$\overline{K} = \frac{1}{4\pi}\int_0^{\pi}\int_0^{2\pi} k^* n(\theta,\psi)\sin\theta \, d\psi \, d\theta \qquad (3)$$

where $n(\theta,\psi)$ is the probability density function of cell orientation with θ being the rotation about the z-axis and ψ being the rotation about the x-axis. It has been shown that $\overline{K} = k^*$ for randomly distributed and oriented cubical cells (n = 1). Since the orientation of the struts on any plane in the middle of the foam is perfectly random, the developed carbon foam is macroscopically isotropic [1,5].

The present model is further modified to consider the fact that carbon struts are not prismatic. The strut is thin toward the center and relatively thick toward the juncture [1,6]; see Figure 3. To this end, a parabolic equation is used to describe the shape of the curved strut, while strut juncture remains cubical in shape. Numerical estimates for the effective thermal conductivity of porous foam with curved struts have been developed.

Results and Discussions

Figure 2 shows the effective thermal conductivity of carbon foam with a porosity of 77% as a function of temperature as well as porosity. The predicted effective thermal conductivitives agree very well with the experimental data when $k_{st} / k_{sl} = 0.25$. The results clearly indicate that the disrupted strut junctures significantly reduce the overall thermal conductivity of the porous carbon foam. In addition, the transverse thermal conductivity of the carbon struts, k_{st}, has very little contribution to the heat conduction in porous carbon foams. It is noted that cubical and spherical cells may give practically similar effective thermal conductivities [2].

In conclusion, the present model accurately predicts the effective thermal conductivity of porous carbon foam in terms of temperature, foam porosity, and morphology.

Acknowledgment

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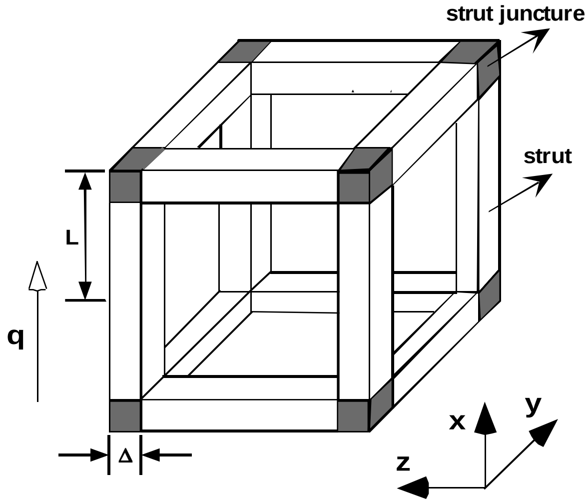

Figure 1: Cubical unit cell.

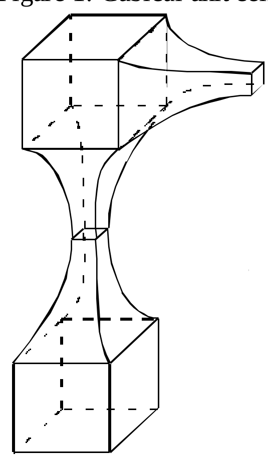

Figure 2: Curved strut and cubical strut juncture.

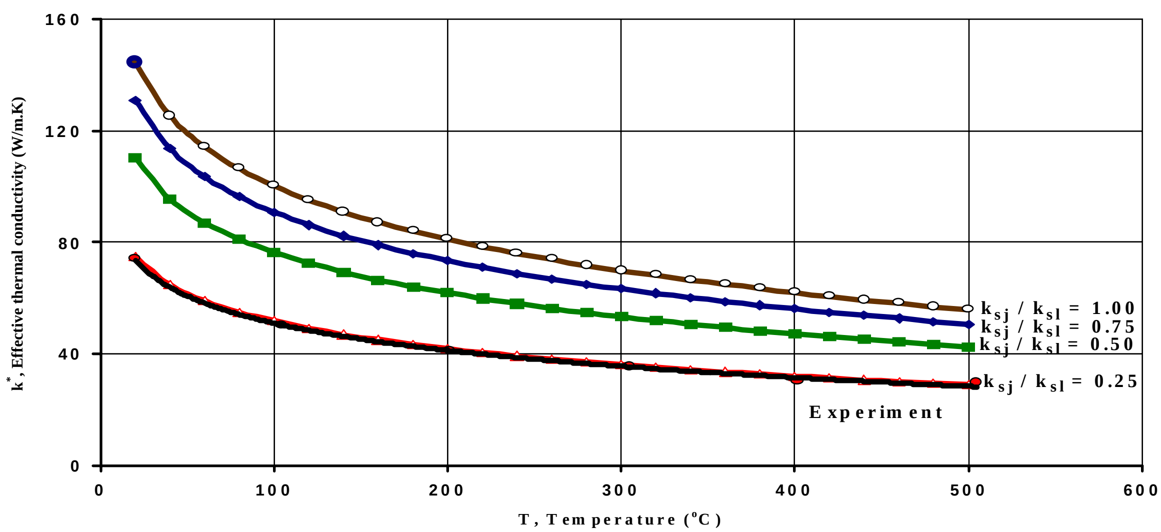

Figure 3: Effective thermal conductivity of carbon foam as a function of temperature for k_{sj} / k_{sl} = 0.25, 0.50, 0.75 and 1.00, k_{st} / k_{sl} = 0.75, and ϕ = 77%.