Heat transfer in syntactyc carbon porous materials

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Abstract. Heat transfer in the syntactic carbon porous materials is considered. A number of assumptions regarding the microstructure of these materials and the corresponding mechanisms of heat transfer are made. Relations to estimate the effective density, heat capacity and thermal conductivity of the materials taking into account the radiant heat exchange between the matrix elements are given. The behavior of these parameters depending on the structure, properties, and components of syntactic porous material is analyzed.

1. Introduction

It is known that carbon materials have unique properties in consequence of which they are widely used in engineering. At present, highly porous carbon foams are of great interest [1-6, 11]. When matrix material of the foam consists of carbon and the hollow microspheres distributed in it, it is syntactic carbon foam (SCF).

In fact, SCFs are heterogeneous systems consisting of carbon, a microsphere shell material, a gaseous medium in the cavity of microspheres, and gaseous or vaporous medium or a fluid impregnating the SCF. A distinctive feature of these materials is that SCF properties can be varied in a wide range by changing the porosity due to the matrix itself, proportions between binding carbon material and the microspheres, their dimensions, the shell material (carbon, ceramics, metal and etc.) the gaseous medium composition. According to what has been said the establishment of behavior regularities of SCF thermophysical properties is of great interest.

2. Body text

At first, we turn to the SCF matrix. If the properties of the microsphere shell material differ from the properties of the carbon, then the matrix can be considered as a porous composite. Let us suppose that in its control volume V_k n_g microspheres with an average volume of cavities V_g are located sufficiently uniformly. It follows that the microporosity of the composite material will be

$$m_g = n_g \varepsilon_g,$$

where $\varepsilon_g = V_g / V_k$ – the fraction of the microsphere cavity volume in the control volume.

Further denoting the fraction of microsphere shell material as $\varepsilon_m = V_m/V_k$, we get $\varepsilon_c = V_c/V_k = 1 - n_g\left(\varepsilon_g + \varepsilon_m\right)$ (V_c – the carbon volume in V_k). Hence the effective density of the porous composite material will be:

$$\rho_k = m_g\rho_g + \rho_{mc}, \tag{1}$$

where $\rho_{mc} = n_g\varepsilon_m\rho_m + \varepsilon_c\rho_c$ – the effective density of the solid phase; ρ_g, ρ_m, ρ_c – density of the gas, microsphere shell material, carbon.

Assuming that in the singled out controlled volume the initial material is three-layered perpendicularly to the direction of heat propagation in order to estimate the effective thermal conductivity λ_{mc} of the layer consisting of microsphere shell material and carbon, we get the dependence:

$$\lambda_{mc} = \left(1 - m_g\right)\bigg/\left(\frac{n_g\varepsilon_m}{\lambda_m} + \frac{\varepsilon_c}{\lambda_c}\right). \tag{2}$$

Here λ_m, λ_c – the thermal conductivity coefficients of the shell material and carbon. Accordingly, the effective thermal conductivity coefficient

$$\lambda_k = 1\bigg/\left(\frac{m_g}{\lambda_g} + \frac{1 - m_g}{\lambda_{mc}}\right), \tag{3}$$

where λ_g – the thermal conductivity coefficient of the gas.

According to the additivity principle the effective specific heat capacity of the porous composite material of the SCF matrix will be ($\rho_g/\rho_k = 1$):

$$c_k = n_g\varepsilon_m\bar{\rho}_m c_m + \varepsilon_c\bar{\rho}_c c_c, \tag{4}$$

where $\bar{\rho}_m = \rho_m/\rho_k$, $\bar{\rho}_c = \rho_c/\rho_k$; c_m, c_c – the specific heat capacity of the microsphere shell material, carbon.

Let us further consider the material of the syntactic foam in general. We suppose that the filtration rate of the medium in the foam pores is small the possible heat transfer due to convection is also small. In addition, we shall not take into account the conductive heat transfer upon contact of the solid and gas (liquid) phases. As a result, the heat conductivity and radiant heat exchange between the more and less heated parts of the matrix are predominant in the SCF provided that the medium in the pores is diathermic [7 – 12].

The noted combination of two types of heat transfer leads to a specific behavior pattern of the SCF material thermal conductivity with temperature increase. In the case when the pores are filled with gas the thermal conductivity is small at low temperatures since the thermal resistance of the spaces between matrix parts is very large, the pores impede heat transfer. As the temperature T increases, the conductivity increases sharply ($\sim T^3$). At high temperatures it becomes of the same order as the thermal conductivity of the matrix material in this case the medium behaves like a solid body whose thermal conductivity is close to the average thermal conductivity λ_k.

In order to take into account the mentioned peculiarities of the heat propagation in the SCF material we select an elementary volume in it and assume that it consists of matrix parts oriented in the direction of the heat flow ξ; parts located transversely to this direction and spaces between them. The pores filled with gas form a series circuit with thermal resistances $R_n = 1/4\sigma\varepsilon_n\gamma_n d_n T^3$ [7, 10], where σ – the Stefan-Boltzmann constant, ε_n – the correction for incomplete blackness of the pores, d_n – the equivalent pore size in the direction of heat propagation, T – the surface temperature of the matrix parts that is close to the average temperature of the SCF material, $\gamma_n = \gamma_n(m_n)$ – a pore shape factor that depends on the porosity m_n ($0 < \gamma_n < 1$).

As a result, after averaging by the elementary volume for the effective thermal conductivity coefficient λ_s, we obtain the formula:

$$\lambda_s = (1-\varphi_n)\lambda_k + \varphi_n / \left(R_k + \varphi_{sn}(R_n + R_k)\right). \tag{5}$$

Here, φ_n – the ratio of the voids area of the cross-section to the heat flow to the total cross-sectional area, φ_{sn} – the ratio of the voids length along the longitudinal line to the total length of the elementary volume in the direction of the heat flow, $R_k = 1/\lambda_k$.

Analyzing the dependence (5) we make sure that as the temperature of the SCF material increases, the thermal conductivity coefficient λ_c increases significantly tending to the theoretical limit $\lambda_{\max} = \lambda_k \left(1 - \varphi_n + \varphi_n / (1 - \varphi_{sn})\right)$. It should be noted that formula (5) is similar to the Lob's formula for cellular bodies. The first term in (5) is due to the longitudinally located matrix parts, the second – the remaining components of the material.

If we consider the heat propagation in the porous body with through holes along the heat flow, then it is easy to see that

$$\lambda_s = (1-m_n)\lambda_k + m_n \left(\alpha_k + 4\sigma\varepsilon_n d_n T^3\right), \tag{6}$$

where α_k – the coefficient that takes into account the convective heat transfer.

Another more natural situation is that heat propagation in the SCF material is modeled using the solid body with through holes which are located chaotically with respect to the direction of the heat flow ξ. In this case, in (5) $\varphi_n = \varphi_{sn} = m_n$ the effective thermal conductivity coefficient

$$\lambda_s = (1-m_n)\lambda_k + m_n / \left(R_k + m_n(R_n - R_k)\right). \tag{7}$$

By definition the thermal diffusivity coefficient of the SCF material

$$a_s = \lambda_s / (\rho_s c_s).$$

Here the effective density ρ_s is approximately equal to

$$\rho_s \cong (1-m_n)\rho_k; \tag{8}$$

effective heat capacity

$$c_s = m_n \bar{\rho}_n c_n + (1-m_n)\bar{\rho}_k c_k \cong (1-m_n)\bar{\rho}_k c_k, \tag{9}$$

where c_n – the material heat capacity of the gaseous phase that is in the pores; $\bar{\rho}_n = \rho_n / \rho_s$, $\bar{\rho}_k = \rho_k / \rho_s$ – relative densities.

As it is known the rate of change of the material average temperature is described by the dependence:

$$c_s \rho_s \frac{\partial T}{\partial \tau} = \frac{d\lambda_s}{dT}(\nabla T \cdot \nabla T) + \lambda_s \nabla^2 T, \tag{10}$$

where τ – time.

In the case where $d\lambda_s / dT$ and the gradient ∇T are small equation (10) is simplified:

$$\partial T / \partial \tau = a_s \nabla^2 T, \tag{11}$$

Where according to (8) – (9)

$$a_s = a_k + \frac{\rho_k / \rho_s - 1}{\rho_s c_s R_k + c_s(\rho_k - \rho_s)R_n}, \quad a_k = \frac{\lambda_m}{\rho_k c_s}.$$

Further, let us suppose that along the surface $\xi = 0$ a heat flow of power q acts upon the selected elementary volume of the material. Assuming that the heat propagates in the ξ axis direction we estimate the heating of the material under consideration, for this we supplement the equation (11) with the initial and boundary conditions:

$$T(\tau = 0) = T_0, \quad -\lambda_s \partial T / \partial \xi \big|_{\xi=0} = q, \quad T(\xi, \tau)\big|_{\xi \to \infty} \to T_0,$$

where T_0 – the initial temperature of the material.

It can be seen that the solution of problem (11), (12) will be:

$$T = T_0 + (2q/\lambda_s)\left((a_s \tau / \pi)^{1/2} \exp\left(-\xi^2 / 4a_s \tau\right) - 0.5\xi^2 F\left(\xi / 2(a_s \tau)^{1/2}\right)\right),$$

where F – the error function.

3. Conclusions

Thus, the relationships for evaluation of thermophysical properties of the specific material of the SCF are obtained taking into account the characteristics of the binding carbon, microsphere shells and the gas contained therein. The formulas for determining the thermal conductivity coefficient, specific heat capacity and thermal diffusivity that can be used at high temperatures are proposed. In addition, alternative dependencies are presented. A solution for the one-dimensional model problem on the heating of the SCF material which clearly illustrates the influence of thermophysical parameters on the temperature change of a given material over time is presented.

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