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Multiphase approach to coupled conduction–radiation heat transfer in reconstructed polymeric foams

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ABSTRACT

Heat insulating properties of polymeric foams at ambient temperature were investigated using the model of coupled heat transfer by conduction and radiation through computer-reconstructed domains. The proposed model considers absorbing and emitting gas and solid phases and partial photon reflection on phase interfaces. The P_1-approximation is used for the description of radiation. For optically thin polymeric walls, the interface conditions are adjusted to account for specular reflection and wave interference effects. The developed model was validated using experimental data and compared with other approaches, including state-of-the-art homogeneous phase approach (HPA). Contrary to HPA, our approach doesn't treat polymeric foams as homogeneous materials with effective properties and provides temperature and radiation gradient fields, which respect foam morphology. The model predicts that the radiative heat flux can account for more than one third of the total heat flux in high porosity expanded polystyrene (EPS) or polyethylene (PE) foams and that the equivalent conductivity of polymeric foam can be significantly reduced by the careful balancing of porosity, cell size, wall thickness and strut content. The presented model doesn't use any empirical correlations and can be used for the optimization of heat transfer in any type of polymeric foam.

1. Introduction

Closed-cell polymeric foams are extensively used by the construction industry as heat insulating materials. The performance of building insulations can be improved by increasing the thickness of the insulation layer, which on the other hand increases the consumption of raw materials, and thus the cost of the entire insulator. Moreover, it is often not possible to increase the thickness of the insulating layer over certain limit. In such a case more efficient insulation material must be used. The effort leading to the improvement of heat insulating properties of polymeric foams is thus of great scientific and industrial importance.

The heat in polymeric foams is transferred by the simultaneous conduction and radiation. Polymeric foams are heterophase materials consisting of solid skeleton and gas cells and both heat transfer modes take place in both phases. Natural convection can be neglected because the viscous forces prevent the air from circulating inside small cells [1,2].

Since the mathematical description of the heat transfer in polymeric foams is quite complicated, many different models were published, each with its own set of simplifying assumptions. Let us provide a brief summary of the most important ones.

The most common is the so-called homogeneous phase approach (HPA), in which the heterogeneous foam is treated as a homogeneous material with effective properties, namely effective conductivity k_{eff}, effective absorption coefficient κ_{eff}, effective scattering coefficient σ_{eff} and effective scattering phase function Φ_{eff}. Once these effective properties are determined, heat transfer can be simulated using any method derived for homogeneous medium. Such methods are well described in previous publications dealing with coupled conductive–radiative heat transfer [3–6]. The result is the equivalent conductivity k_{eq}, which comprises the contributions of both conduction and radiation.

The effective conductivity k_{eff} can be estimated by analytical or numerical methods. A simple explicit expression is provided by Hilyard and Cunningham [7]

$$k_{\mathrm{eff}} = \varepsilon k_{\mathrm{gas}} + (1-\varepsilon)\left(\frac{2}{3}-\frac{f_s}{3}\right)k_{\mathrm{sol}}, \tag{1}$$

where ε is the porosity, f_s is the fraction of the polymer located in the struts, k_{gas} and k_{sol} are heat conductivities of the gas and the

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solid phases, respectively. Struts are thick zones of polymer phase located around edges and vertices of polyhedral closed cells. Eq. (1) can be also adapted to incorporate other aspects of foam morphology, for example, the foam anisotropy. The summary of analytical methods for estimating k_{eff} can be found in Öchsner et al. [8].

Numerical approaches for the determination of effective conductivity k_{eff} are based on the simulation of conductive heat transfer in the domain of reconstructed material. These methods essentially treat a pure conduction problem using the multiphase approach (MPA). In MPA, each phase retains its physical properties, transport equations are defined separately for each phase and linked together on the interfaces. Numerical methods are often based on finite volume method [9–12] or lattice Boltzmann method [13]. The advantage of numerical methods is that they are more general and respect the foam morphology. The disadvantage lies in their high demands on computational resources.

Effective radiative transport properties for homogeneous phase approach can be calculated as the sum of contributions from walls and struts. This model was first used for foams consisting of dodecahedron cells [14]. Similar approach was later used to study also foams with cubic and tetrakaidecahedron cells [15–17]. Radiative properties of foams with tomography-reconstructed cells were studied first for open cell metal foams [18,19] and then for closed cell polymeric foams [20]. Very recently, effective radiative properties have been calculated from Voronoi's foam with random structure [21]. The summary of methods using HPA can be found in Baillis and Sacadura [22] and more recently in Baillis et al. [23].

Talukdar et al. [24] recently proposed coupled conduction–radiation model using MPA suited for metal foams, which don't transfer heat by radiation in solid phase. It was later compared to models, which use HPA, by Mendes et al. [25].

Studies using MPA exist for pure conduction [9–13] or pure radiation [26,27] transfer in foams, but to the best of our knowledge, publications using MPA to coupled conduction–radiation transfer in porous media are limited to metal foams [24,25], which don't transfer heat by radiation in solid phase. The advantage of using the MPA is that it provides equivalent conductivity k_{eq} directly without the need for special methods, which estimate effective properties of homogeneous medium and which could bring additional errors [25].

The aim of this paper is to develop the first comprehensive mathematical model that describes the coupled conductive and radiative heat transfer in both phases in computer-reconstructed three-dimensional (3D) polymeric foams. The presented model is based only on fundamental laws of heat transfer and not on empirical correlations. Thus, no input data other than the physical properties of pure phases and the detailed description of foam morphology is required for the model. Although the model slightly suffers from its high computational demands at this time, it opens a new, rigorous way of studying the coupled conduction–radiation heat transfer in porous media.

2. Mathematical model

In this paper, we consider only steady-state heat transfer by conduction and radiation. We treat polymeric foams as heterogeneous media, thus we need to specify governing equations for each phase supplemented by boundary conditions at phase interfaces and computational domain boundaries.

2.1. Governing equations in each phase

The attenuation of radiation inside each phase is in our model described only by one parameter – absorption coefficient κ, which is taken to be gray, i.e., independent of the wavelength. The assumption of gray medium was tested for the considered polymeric foams against spectrally-resolved description by Ferkl et al. [28] and the difference was found to be negligible. Scattering of radiation by molecules or possible impurities is neglected in the presented version of the model. However, scattering on phase interfaces is incorporated in the model (see Section 2.3).

The size of the foam cells is assumed to be much larger than the mean free path of gas molecules, and similarly, the thickness of the walls is assumed to be much larger than the mean free path of phonons. In this case, the Fourier law is valid, and thus can be used to describe the conductive heat flux.

Energy conservation equation for the general three-dimensional medium can be written as

$$\nabla\cdot(\mathbf{q}_{tot}) = \nabla\cdot(\mathbf{q}_{con} + \mathbf{q}_{rad}) = 0, \tag{2}$$

where $\mathbf{q}_{tot}$, $\mathbf{q}_{con}$, $\mathbf{q}_{rad}$ are the total, conductive and radiative heat flux, respectively.

The conductive heat flux is described by the Fourier's law as

$$\mathbf{q}_{con} = -k\nabla T, \tag{3}$$

where T is the temperature and k is the thermal conductivity of the given phase (polymer or gas).

The divergence of the radiative heat flux can be written as [3]

$$\nabla\cdot\mathbf{q}_{rad} = \kappa\left(4n^2\sigma T^4 - G\right), \tag{4}$$

where σ is the Stefan–Boltzmann constant, n is the real part of the refractive index and G is the incident radiation. The incident radiation is the direction-integrated intensity of radiation.

By combining Eqs. (2)–(4), we obtain the energy conservation equation with two state variables – temperature T and incident radiation G:

$$k\Delta T = \kappa\left(4n^2\sigma T^4 - G\right). \tag{5}$$

For the sake of convergence, it is advantageous to linearize Eq. (5) in the form

$$k\Delta T = \kappa\left(4n^2\sigma\left[T^{*4} + 4T^{*3}(T - T^*)\right] - G\right), \tag{6}$$

where T^* represents the value of temperature in the previous iteration.

The second differential equation for the incident radiation G is obtained using the so-called P_1-approximation [3]. Neglecting the scattering, it can be written as

$$\frac{1}{\kappa}\Delta G = 3\kappa\left(G - 4n^2\sigma T^4\right). \tag{7}$$

Eqs. (6) and (7) create a system of two partial differential equations. The solution process consists of guessing the temperature profile, solving Eq. (7) for incident radiation profile, substituting this profile to Eq. (6) and solving Eq. (6) for new temperature profile. This procedure is repeated until two subsequent temperature profiles are practically identical.

2.2. Boundary conditions

Let us now assume that the polymeric foam sample is in the shape of a block with dimensions of L_x, L_y and L_z (see Fig. 1). Let us further assume that the foam sample is enclosed from two opposite