
16 Thermal Transport in Highly Porous Cellular Materials

Raymond Viskanta

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16.1 INTRODUCTION

Highly porous cellular materials and foams have many interesting combinations of physical, mechanical, electrical, and thermal properties such as high stiffness, thermal and electrical conductivity, and flow permeability along with low specific weight. The development of plastic, metallic, and ceramic highly porous materials [1–3] has enabled and improved the performance of aerospace, chemical, energy, industrial, thermal, and other technologies. Of primary interest in this discussion are cellular materials (foams) of high porosity ($\phi > 0.8$) that are finding increased uses in thermal management applications such as thermal insulations [4], heat exchangers [5–7], solar energy collection and storage [8,9], hydrogen storage [10], wicks for heat pipes [11], energy conservation/waste heat recovery [12], burners for combustion enhancement [13,14], cooling systems [15], thermal control of electronics [16,17], thermal protection systems (TPS) [18], and many others. Foams have

high porosity, large surface area per unit volume, large heat transfer coefficient, and large radiation extinction coefficient and offer low-pressure drop for flow.

Cellular materials of interest here are primarily of two types: (1) closed-cell and (2) open-cell foams. Among the most common closed-cell foams are the expanded polystyrene (EPS) and polyurethane foams. The expanded foams consist only of walls, whereas extruded polystyrene (XPS) and polyurethane foams are formed by walls and struts. Open-cell carbon, metallic, and ceramic foams have a reticular structure. The bulk material is entirely concentrated on the cell sides shaping the struts. The solid matrix is made of struts oriented in different directions in space. The strut thickness is always much smaller than the cell diameter. Both closed-cell and open-cell foams have a wide range of uses [1–3], but this account is primarily concerned with thermal management applications.

Thermal design and operation of components and devices for modern technology that use cellular materials require both qualitative and quantitative knowledge of flow and heat transfer in such materials. The aim of the present overview is twofold: first, to briefly discuss the predictive models for describing the flow, thermal, and radiative processes in cellular porous materials and second, to apply the models for predicting heat transfer in different physical situations. The scope of this overview does not permit detailed discussion; hence, the main focus is to identify for the interested reader up-to-date references dealing with flow and heat transfer in closed-cell and open-cell foams from low to high temperatures. The discussion to follow is restricted to porous materials with random and not with regular structures and with submillimeter and/or larger mean pore (cell) diameters. The solid is inert, and there are no chemical reactions in the fluid; while phase change (i.e., boiling, condensation, solidification, and melting) of the fluid may be of interest for some applications [19], it is not considered in this account.

16.2 OVERVIEW OF TRANSPORT IN POROUS MATERIALS

For design analysis and optimization of transport phenomena in complex chemical, energy, and thermal technologies utilizing highly porous cellular materials, increasingly sophisticated computational modeling capabilities have been developed during the last few decades [20]. The complex phenomena include the transport of mass, momentum, and energy due diffusive and advective motion of the fluid, which are combined with conduction and radiation transport in the confining and embedded solids. The modeling of the relevant transport processes is accomplished on different levels of sophistication. In the analysis of flow through porous media, the model equations are fully derived from more rigorous formulations such as the Navier–Stokes equations by local volume averaging, homogenization, and/or simply from empirical observations. The pseudo-homogeneous approach requires that mean flow quantities be defined on a reasonably sized representative elementary volume [20–22]. The models may be applied if the scales of the system under consideration are significantly larger than the pore size of the porous media.

Transport processes in porous materials may be modeled using two major classes of approaches: (1) a macroscopic approach, where volume-averaged semiempirical equations are used to describe flow and transport characteristics, and (2) a microscopic approach, where small-scale flow and transport details are simulated by considering the specific geometry of the porous medium. In general, heat transfer in a porous material occurs by conduction, convection, and radiation, and the interactions of flow and the three modes of energy transport are illustrated schematically in Figure 16.1. If the cells of the porous material are closed, there will be no throughflow of the fluid, and if the cells are small in diameter, natural convection in the fluid contained in the cells can also be neglected.

Three different types of models have been proposed and are being used to analyze transport in porous materials. They include the following: (1) local thermal equilibrium (LTE) with a homogeneous single fluid and solid temperature (i.e., one-energy equation) model, (2) local thermal nonequilibrium model with separate fluid and solid temperatures (i.e., two-energy equation model), and (3) lattice Boltzmann model. The Boltzmann method is a powerful and sophisticated technique for the computational modeling of complex fluid flow problems, including single and multiphase flow in porous