

SPECIFIC FEATURE OF THERMAL AND ELECTRICAL TRANSPORT IN CELLULAR MEDIA

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ABSTRACT

This paper presents a brief survey of the electrical and thermal properties of cellular materials. Some applicable engineering forms based on composite and percolation theories are highlighted and its verification by computer modeling is also mentioned.

1. INTRODUCTION

Foams or cellular structure materials exhibit a new class of structural materials that combine many advantageous behaviours for future application. Generally the cellular structure materials keep the advantages of bulk material with the structural advantages of low density, relative high stiffness, and adjustable cell structure [1]. Foams are attractive in a number of engineering applications including impact energy absorption systems, sound absorbers, compact heat exchangers, electrical and thermal insulators, electromagnetic wave shields; nickel foam based high-power batteries and fire walls. These applications are based on the recent technological advances of foam manufacturing processes leading to relatively low cost improved performance materials. Understanding the behaviours of open or closed cell foams is still not closed even a lot of experimental and theoretical works has been published. Among them, this work is going to focus on transport (thermal and electrical) properties of cellular materials, and emphasise the special characters originated from the porous structure. The question of conductivity in cellular system can be approached by the two-phase composite concept where the continuous solid phase a continuous or discontinuous gas phase (open or closed porosity) is presented. Many results are earned from empirical generalizations and different computer models of idealized 2D cell structure (prescribed geometrical features including cell shape and size distribution with imperfections) works well to fit the experimental measurements. The solid phase conductivity is also a hierarchical level since looking at the microstructure of the cell wall material it is a composite system. The cell wall microstructure has an important role at the foaming process to get a stable cellular structure during solidification.

2. THERMAL TRANSPORT

In a cellular system many factors could be consider to explain the measured heat flow values. The combination of conduction through the solid phase, conduction through the enclosed gas, convection within the cells and radiation through the cell walls and across the cell voids usually give a complex heat flow, which is described by an effective thermal conductivity. At steady state situation the thermal conductivity, λ [W/mK], is defined by Fourier's law: the heat flux, q [w/m²], induced by a temperature gradient, ∇T , is: $q = -\lambda \nabla T$.

In non-steady state conduction the cumulative heat flow of a small element is nonzero causing its temperature change, with time, t , at location of x coordinate (in 1 D) according to the heat diffusion equation:

$$\rho C_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x} \left(\lambda \frac{\partial T}{\partial x} \right)$$

If the properties of mass density, ρ [kg/m^3], specific heat, C_p [J/kgK], and heat conductivity are constants in the temperature range of our interest, the heat diffusion equation becomes a function of one variable, thermal diffusivity (α [m^2/s]) parameter: $\alpha = \lambda / \rho C_p$. The specific heat for two-phase composite would be a sum of the specific heat of each phase multiplied by its weight fraction. Because the gas has negligible weight even in extremely low density foams the specific heat of the foam is practically equals the value of the solid from which it is made. Therefore the heat conductivity is a key parameter for any thermal process, and usually its temperature dependence and mass density values display the thermal applicability of certain foam. For cellular materials the porosity, p , is also a measurable and characteristic parameter.

For the porosity the connection with mass density is simple as: $p = \left(V - \frac{m}{\rho} \right) / V = 1 - \frac{\rho^*}{\rho}$,

where V is the volume, ρ and ρ^* are the solid and foam density, correspondingly. Most of the models count with solid, λ_s , and gas, λ_g , conduction as [2,3]:

$$\lambda = \xi \left(\frac{\rho^*}{\rho} \right) \lambda_s + \left(1 - \frac{\rho^*}{\rho} \right) \lambda_g$$

where the tortuous shape of cell walls is included in the efficiency factor, ξ .

Several theories have been developed to describe the combined thermal conductivity in terms of two limiting cases, the “parallel-series” arrangement of the solid and gaseous constituents. The parallel and series cases are given by [4] :

$$\lambda_{parallel} = p \lambda_{gas} + (1 - p) \lambda_{solid} \quad \text{and} \quad \lambda_{series} = \frac{\lambda_{solid} \lambda_{gas}}{p \lambda_{solid} + (1 - p) \lambda_{gas}}$$

The two limiting cases are typically combined in two ways. One approach assumes that combined thermal conductivity can be obtained by a superposition of the parallel and series arrangements.

$$\lambda = A \lambda_{parallel} + (1 - A) \lambda_{series}$$

where A is the fraction of heat transfer in parallel mode and $(1 - A)$ is in series mode. The other approach assumes that combined conduction thermal conductivity is the square root of the sum of the squares of the two limiting cases:

$$\lambda = \sqrt{A \lambda_{parallel}^2 + (1 - A) \lambda_{series}^2}$$

Until now we considered only two conduction contributions, but depending on the application temperature and pore size distribution of the foam the convection of gas in the cells and radiation with its scattering through the porous structure should be counted, as well.

Convection usually can be eliminated, it is important only when the Grashof number (dimensionless parameter of the natural convection is described by the ratio of the buoyant force driving the flow to the viscous force opposing it) is greater than about 1000 [5]. The Grashof number is obtained by the formula:

$$Gr = \frac{g\beta \Delta T_c l^3 \rho^2}{\mu^2}$$

where the g is the acceleration due to gravity, β is the volume coefficient of expansion for the gas (in ideal gas approximation $\beta=1/T$), ΔT_c is the temperature difference across the l size cell, and ρ and μ are the density and the dynamic viscosity of the gas, respectively. Using data suitable to air the critical cell size is about $l=10$ mm which above the convection has to be considered. The size of cells in real foams is smaller than this, so the convection can be suppressed completely. Radiation is a highly nonlinear process because its temperature dependence described by the Stephan's law: $q_{rad} = \varepsilon\sigma T^4$, where T is the temperature of the ε emissivity surface ($0 \leq \varepsilon \leq 1$) and σ is the Stephan's constant ($5,67 \times 10^{-8} \text{ W/m}^2\text{K}^4$). If the foam is inserted between two different temperature surfaces (with T_L lower and T_H higher temperatures) with L distances, the net radiation between the plates will be:

$$q_{rad} = q_{rad}^0 \exp\left(-K_s \frac{\rho^*}{\rho} L\right)$$

where the $q_{rad}^0 = \varepsilon\sigma(T_H^4 - T_L^4)$ radiation in vacuum is supposed to be attenuated by the cell walls absorption of the inserted foam approximately by the Beer's law with K_s [1/m] extinction coefficient [2]. The extinction coefficients include the cell structure which governs the inherent radiation view factors, emissivity and transparency of cell walls depending on wall thickness and materials. It can be observed that a low foam density increase the radiation, because radiation is reflected less often in a cellular structure with large cells. Considering a thermal equilibrium and taking the Fourier's law we can evaluated the corresponding radiation conductivity as:

$$\lambda_{rad} = 4\varepsilon\sigma T_m^3 t \exp\left(-K_s \frac{\rho^*}{\rho} L\right)$$

using the approximation of $\frac{dT}{dx} = (T_H - T_L)/L = \Delta T/L$, and $T_H^4 - T_L^4 \approx 4 \Delta T T_m^3$, where T_m is a mean temperature of the foam, $T_m = (T_H + T_L)/2$.

The finite element method is a powerful tool to calculate the radiation heat transfer in a well defined cellular structure, such as 2D regular honeycomb [6]. The radiation view factors between the cell walls can be calculated by established algorithms. From finite element analysis concerning the radiation conductivity the same formula was verified, where the emissivity of the "grey-body" cell material was taken as uniform and independent of temperature. Diffusive reflections were assumed and gas attenuation was ignored. Modeling results showed that $\lambda_{rad} \propto \varepsilon\sigma T_m^3 l$, where λ_{rad} showed linear tendency with l cell size. The total or apparent thermal conductivity is a result of the competition of the above detailed four contributions. For polymer foams the thermal conductivity shows a minimum value as a function of foam density which is an interesting example for analysis. At large density the solid conduction (cell walls) dominates with increasing weight, the low gas conduction gives less contribution. As decreasing the density the radiation is more important since the foam getting transparent and partly the larger cell cavities let the convection to begin. Temperature itself changes the conductivity, but in a complicated way [7, 13-15], usually the conductivity shows a monotone increasing behavior, somewhere with plateau or local minimum on the curves (see figure 1. and 2.). It is worth to mention that the thermal conductivity is affected by the age too. Many types of foam are blown using low conductivity gases, such as CCl_3F .

During their application the enclosed gas diffuses out of the cells substituted by air with higher gas conductivity. If the structure is intensively loaded this leads to cell wall rupturing and the conductivity rises faster [2].

The fire resistance and thermal shock resistance of foams are exploited in firebrick and other low-density refractory and novel materials such as *Al* based metal foams. The thermal shock resistance, ΔT_C , is measured by the temperature drop difference suddenly applied to the surface what the surface can stand without cracking due to thermal stresses. The thermal shock resistance varies with the foam density as, $\Delta T_C \propto (\rho^* / \rho)^{-1/2}$ [2]. As the density of foam decreases the network of struts which make up the cellular structure can accommodate the thermal strain by bending, leading to better thermal shock resistance. Thermal fire resistance τ of foam is often described by the time to failure of the unexposed surface by excessive heat transmission (constant peak temperature or heat flux) exposed to the front surface. During this time the temperature increases in the foam structure and the foam lost its insulating capability. This behavior is strongly affected by the Biot number $Bi=hL/\lambda$, where L the width of the insulating foam, h is the heat exchange coefficients at the unexposed surface. A low (apparent) thermal conductivity is beneficial as it prolongs the time needed for the temperature of the unexposed surface to reach the failure temperature. In case of *Al* alloy foams the fire resistance is enhanced by the oxide layers covering each cell wall. The oxide coating will not collapse even if their cores have melt exceeding the melting temperature of bulk alloy [6].

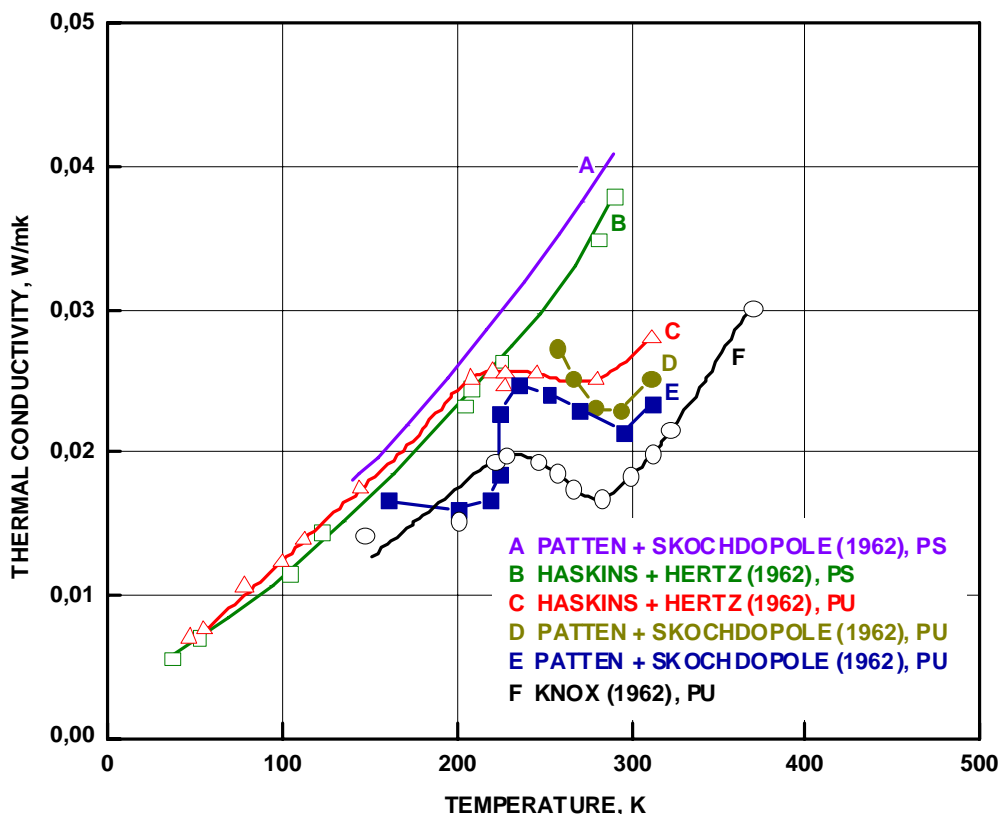


Fig. 1. Thermal conductivity of foams as a function of temperature (polystyrene, PS [13, 14]; polyurethane, PU [13-15]; after Gibson and Ashby in Ref. [2].

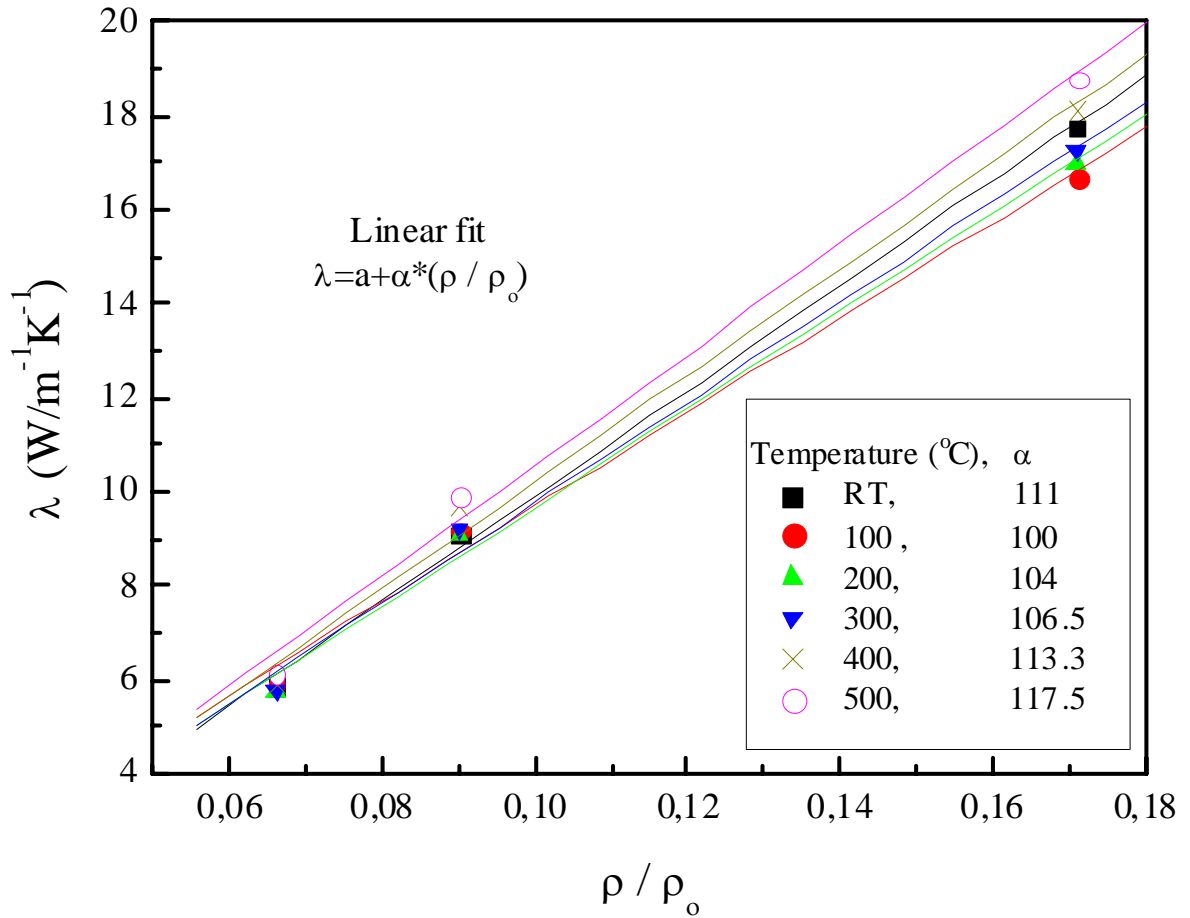


Fig. 2. Thermal conductivity vs. different relative density of closed cell Alporas foams at different temperatures ($T [C^{\circ}] = \text{room temp.}, 100, 200, 300, 400, 50$) [7]. The linear slope agrees with the solid-gas composite conductivity, while at low relative density the radiation generated negative slope tail (as known for polymers) is absent because of limited sample density reduction. Note, the slope parameter of linear fits vs. temperature shows the same character as displayed in Fig. 1.

3. ELECTRICAL TRANSPORT

The value of the electrical conductivity σ^* of foams is useful in the applications of insulating coatings, mounting panel for electrical components and protective dome of a radar guidance system. The sensitivity of electrical conductivity on changes in cellular structure has been successfully used to monitor imperfections, crack initiation and propagation in metal foams.

The electric conductivity is related the conductivity in a two-phase composite to the conductivity of continuous solid phase and a continuous or discontinuous gas phase, as well. Some expressions are evaluated from empirical observation while others emerge from consideration of the structure of the foam. However, the formulae that describe the dependency of electrical properties on the density, cell structure and porosity are still limited.

A theoretical calculation considering an octahedral array of wires has been suggested by following formula as [8]:

$$\sigma^* = \frac{1-p}{3(1-0.121(1-p)^{1/2})} \sigma_s$$

where σ_s is a solid conductivity for open type porous body. For closed cell foams, the connection between electrical conductivity and porosity is: $\sigma^* = (1-1.5p)\sigma_s$, where the porosity is limited to low value.

Others showed that the conductivity vary as [9]: $\sigma^* = 2K \frac{1-p}{(2K+p)} \sigma_s$, where K is a constants

determined by the cell structure, when the shape of the cell is spherical with $K=0.3$.

Percolation theory gives a powerful approach to evaluate the electric conductivity [10]. Here foam is considered as an “infinite” cluster, where there are a lot of continuous current paths along cell walls carrying out electric measurements. So the structure is conductive above the percolation threshold P_c . The effective properties ξ , which we are interested in (in this case the electric conductivity) becomes zero at the percolation threshold, while near P_c it behaves as a power of $\xi \propto (P - P_c)^v$, where P is a volume fraction of the relevant component and v is a dynamic exponents. In the foam structure, P is taken as density, and the threshold can be fixed at zero density ($P_c=0, \rho=0$), where there are surely no solids to conduct current. So we can write the power law expression as [11]:

$$\frac{\sigma^*}{\sigma_s} = K \left(\frac{\rho^*}{\rho_s} \right)^v$$

where ρ^*/ρ_s is the relative density and the value K as a constant should be 1, since for $\rho^*=\rho_s$ the effective property $\sigma^*=\sigma_s$. As the relative density decreases, the average cross-sections available for conduction decreases and the tortuosity of the current path increases, thus the resistivity increases. Experimental investigations on aluminum alloy foam are in good agreement with the percolation theory; the power law expression well fits the measured electrical conductivity vs. relative density curves with dynamic exponents about $v=1.5$. For two dimensions the $v=1.3$ is well established [12]. In three-dimensional case the dynamic exponents are reported from 1.5 to 2. It is interesting to note that at constant relative density the cell diameter seems to have a minor influence on the electrical conductivity of foams, while itself the density can influence it [11].

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