

Thermal Conductivity of Open-Cell Polyolefin Foams

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ABSTRACT: The thermal conductivity and the cellular structure of novel open-cell polyolefin foams produced by compression molding and based on blends of an ethylene-vinyl acetate copolymer (EVA) and a low-density polyethylene (LDPE) have been studied in the temperature range between 24 and 50 °C. The experimental results have shown that the cellular structure of the analyzed materials has interconnected cells because of the presence of large and small holes in the cell walls, this structure being clearly different to the typical structure of open-cell polyurethane foams. It has been found that at low temperatures the materials have a slightly higher thermal conductivity than closed-cell polyolefin foams of similar densities. The different mechanisms of heat flow, conduction, convection, and radiation have been analyzed by using experimental measurements and a theoretical model. It has been proved that, in spite of having an open-cell structure, the convection mechanism is negligible, being the radiation mechanism the one which made different the conductivity of materials with varying cellular structures. © 2007 Wiley Periodicals, Inc. *J Polym Sci Part B: Polym Phys* 46: 212–221, 2008

Keywords: ethylene-vinyl acetate copolymer; foams; open-cell foams; polyethylene; polyolefins; thermal conductivity; thermal properties

INTRODUCTION

The aim of thermal insulation is to reduce heat transfer between a medium and its environments. Of all insulating materials like powders, fibrous boards, multilayer systems, vacuum panels, etc, the main advantage of polymer foam is that these materials have a low cost and they are, in general terms, easy to produce and maintain. Because of these advantages, closed-cell polymeric foams are the most widely used thermal insulators in engineering applications.

It is well known^{1–3} that heat transfer through a foam is a consequence of four mechanisms: convection in the gas phase, conduction along the struts and cell walls of the solid polymer,

conduction through the gas within the cells, and thermal radiation. The estimation of the relative contributions of each heat transfer mechanism is an important key to identify the main factors that might decrease the thermal conductivity while keeping the density fixed at a reasonable value. Because of this reason this subject has been approached by different authors mainly for the case of the closed-cell materials.^{1–20}

Closed-cell foams have the lowest thermal conductivity of any conventional nonvacuum insulator. The low-volume fraction of the solid phase, the small cell size that eliminates convection and reduces radiation (though absorption, scattering and reflection at the cell walls), and the low conductivity of the enclosed gas are the physical basis for this low-thermal conductivity. Within these closed-cell foams, rigid polyurethane (PU) foams are the most popular foam insulator, because they have low-thermal conductivity, high strength-to-weight ratio, good

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mechanical strength, and low cost, however they cannot be used in acid or alkali environments. Other types of foam used in these applications are polystyrene foams (PS), polyimide foams, phenolic resins, and polyolefin foams. Cross-linked closed-cell polyethylene foams (PE) are good electrical insulators, are thermo-formable and do not absorb moisture and water.

Several processes are used nowadays to produce crosslinked polyolefin-based foams.^{21–25} All these well-known technologies give rise to foams with closed cells. However, because of the low-acoustic absorption and poor recovery after creep of these foams, open-cell polyolefin-based foams have been recently introduced into the market.^{26–28} The change of the type of cellular structure (from closed cells to open cells) introduces a dramatic modification of the physical mechanisms controlling the physical properties. Regarding thermal conductivity, it is expected a higher contribution of the radiation mechanism and a possible contribution of convection because of the interconnected cellular structure. As a consequence, a worse thermal insulation is expected for these materials. However, as far as we know, these expected effects have not been studied in detail and in fact it is not clear if these new open-cell materials could be used as thermal insulators.

Taking the previous ideas in mind this article presents a systematic study on the thermal conductivity of a collection of open-cell polyolefin foams. The aims of the investigation are, on the one hand, to adapt and apply the nowadays developed concepts and models for closed-cell foams to open-cell materials in order to quantify the weight of each thermal conduction mechanism in the whole conductivity. On the one hand, the article analyses if the new open-cell foams are interesting materials for thermal insulation.

THEORETICAL BACKGROUND

The main models used in the article are introduced in this section.

As it has been previously mentioned the heat transfer through a foam is a consequence of several mechanisms: convection in the gas phase (λ_{cv}), conduction along the struts and cell walls of the solid polymer (λ_s), conduction through the gas within the cells (λ_g), and thermal radiation (λ_r). Many of the early works in this field postu-

lated that the effective conductivity of the foam (λ) could be expressed by a superposition of the different mechanism taken separately.^{1–3}

$$\lambda = \lambda_s + \lambda_g + \lambda_r + \lambda_{cv} \quad (1)$$

This concept is an accurate approximation except for cases in which low-emissivity boundary layers are used. In that case the actual effect on the foam conductivity will be far less than predicted by assuming that radiation acts independently of the other heat transfer mechanisms.¹

Several investigations have showed that a good approximation to the conductivity by conduction for low-density foams can be obtained by using the equation.^{1,8}

$$\lambda = \lambda_s + \lambda_g = \lambda_{gas} V_{gas} + \lambda_{solid} \left(\frac{2}{3} - \frac{f_s}{3} \right) V_s \quad (2)$$

where λ_{gas} is the thermal conductivity of the gas which fills the cells, λ_{solid} is the thermal conductivity of the matrix polymer, V_{gas} is the volume fraction of gas, V_s is the volume fraction of polymer, and f_s is the fraction of solid in the foam edges. The main elements of the cellular structure in a foam are the cell walls and the cell edges; f_s measures the mass of polymer in the edges relative to the total mass of polymer in the foam. This simple equation accounts for the contribution of the gas phase (first term) and for the conduction of the solid phase (second term). In this equation the term f_s is a measure of the open-cell content in the foam, foams with all the cells interconnected usually present high values of f_s .

On the other hand, convection in closed-cell foams is only important when the Grashof number (which describes the ratio of the buoyant force driving convection to the viscous force opposing it) is greater than about 1000.⁴ The Grashof number is given by:

$$Gr = \frac{g\beta\Delta T_c \phi^3 \rho^2}{\eta^2} \quad (3)$$

where g is the acceleration due to gravity, β is the volume coefficient of expansion of the gas (for an ideal gas $\beta = 1/T$), ΔT_c is the temperature difference across one cell, ϕ is the cell size, and ρ and η are the density and dynamic viscosity of the gas. It is widely accepted that convection plays a minor role in heat transfer in closed-cell materials, provided the cells are less than 4 mm in diameter.²⁹

The radiation contribution has also been studied by several authors: Glicksman,¹ Williams and Aldao,¹⁴ and Boetes and Hoogendoorn.³⁰ One of the most accepted models is the Roseland one. In this approximation the material is considered as optically thick.¹ Foams in real applications are usually thick enough (several millimeters thick) to fulfill this approximation. Therefore the radiative flux can be approximated introducing a radiative conductivity given by:

$$\lambda_r = \frac{16n^2\sigma T^3}{3K_R} \quad (4)$$

where n is the effective index of refraction, σ is the Stephan-Boltzmann constant, T is the temperature and K_R is the Rosseland mean extinction coefficient. For polymer foams n is close to 1 and K_R can be obtained by using the following equation:

$$\frac{1}{K_R} = \frac{\int_0^\infty \frac{1}{K_\lambda} \frac{\partial e_{b,\lambda}}{\partial T} d\lambda}{\int_0^\infty \frac{\partial e_{b,\lambda}}{\partial T} d\lambda} = \int_0^\infty \frac{1}{K_\lambda} \frac{\partial e_{b,\lambda}}{\partial e_b} d\lambda \quad (5)$$

where, $e_{b,\lambda}$ is the spectral black body emissive power and λ the wavelength. The Rosseland mean extinction coefficient is an average value of K_λ (extinction coefficient for the wavelength λ) weighed by the local spectral energy flux. Once K_λ is measured, by using infrared spectroscopy (see experimental section), it is possible to obtain K_R from the above equation, and then calculate the radiative conductivity from eq 4.

EXPERIMENTAL

Materials

The foams studied were manufactured by using the two-stage molding procedure, using azodi-carbonamide as foaming agent, dycumil peroxide as crosslinking agent, and calcium carbonate as filler.^{22,25} After the foams blocks are produced, the cells are opened by mechanical deformation. This procedure^{26–28} allows obtaining a 100% open-cell polyolefin-based foam. The mechanical deformation is applied by passing the original foam block, of 11 cm in thickness, through two cylindrical rolls separated (in the direction of the block thickness) a smaller distance (6 cm)

Table 1. Main Characteristics of the Analyzed Foams

Foams	ρ_f (kg/m ³)	ϕ (μ m)	f_s
CA23	23.1 \pm 1.3	3,294 \pm 185	0.51 \pm 0.08
CA26	26.1 \pm 0.2	630 \pm 52	0.55 \pm 0.07
CA29	28.5 \pm 1.4	1,053 \pm 87	0.59 \pm 0.01
CA33	33.2 \pm 0.3	1,390 \pm 98	0.57 \pm 0.06
CA44	43.6 \pm 1.5	970 \pm 75	0.58 \pm 0.07
CA49	48.7 \pm 1.6	1,011 \pm 88	0.53 \pm 0.06
CA64	64.9 \pm 1.9	3,017 \pm 167	0.52 \pm 0.07

than the block thickness. Therefore, the foam is deformed both in compression and shear producing the rupture of the cell walls. The block is passed several times through this mechanical system to assess a 100% open-cell structure.

The samples of this study were cut from the central part of the blocks to avoid possible effects related to the typical inhomogenous cellular structure of the blocks produced from this technology.^{8,31}

The foams are blends of an ethylene-vinyl acetate copolymer (EVA, VA content 18%) and a low-density polyethylene (LDPE). The chemical composition of the materials was 40% LDPE, 40% EVA, and 12% CaCO₃. All the foams present a proportion of foaming agent residues of ~7%. The remaining 1% contains the activator for the blowing agent (ZnO) and processing aids. The gel content was determined in xylene at 140 °C during 24 h according to standard procedures for polyolefins. The measured values were constant for all the materials under study being the average value 59% \pm 3%. Table 1 shows the main characteristics of the foams under study that were kindly supplied by Sanwa Kako, Kyoto, Japan.

Foams Characterization

Density

The foams density was obtained as the ratio between mass and volume of the sample.

Foam Morphology

Scanning electron microscopy (SEM) was used to characterize the cell size and the cell wall thickness of the foams. Micrographs were taken using a JEOL JSM-820 microscope.

The mean cell size (ϕ) in each foam direction (x , y , z) was estimated using the intersections

method, which consists of measuring the number of cells that intersected several reference lines, dividing the appropriate reference length by the number of cells. The average cell size for each foam was computed as a mean value of the cell sizes in the different directions. All the foams were isotropic, so it was not necessary to analyze the anisotropy coefficients. Taking into account the relationship between the mean-measured length of the randomly truncated cells and the real diameter of the cell, the previous result was multiplied by 1.623.³² The fraction of mass in the struts (f_s) was obtained by means of the method suggested by Kuhn et al.¹⁵

Thermal Conductivity

The conductivity measurements were carried out under steady-state heat flow conditions through the test sample in accordance with ASTM C518 method. The equipment is based on the Fourier's law. The transducer of the heat flow is a square thermocouple of 10 cm of side, with a sensitivity of $40 \mu\text{V}/^\circ\text{C}$, which is localized in the central portion of the bottom face of the equipment. The total face area is a square of $30 \text{ cm} \times 30 \text{ cm}$ side, the remaining portion acting as a shield that keeps the heat flow uniform in the measuring central section. The method is not absolute, and therefore calibration is necessary using a standard sample. Once, this has been done, the heat flow per unit area (q_T) can be measured in the heat flow transducer, and the thermal conductivity of the sample (λ) can be calculated using eq 6 as follows:

$$\lambda = LN \left(\frac{q_T}{\Delta T_m} \right) \quad (6)$$

where L is the sample thickness, N is a calibration factor, and T_m is the mean temperature.

Square samples of $30 \text{ cm} \times 30 \text{ cm}$ side and 10-mm thick were used in all the experiments. Test was carried out at average temperatures of 24, 30, 40, and 50 °C, being the temperature difference between plates 30 °C. The main part of the experiments was conducted with the upper plate being the hot plate. Additionally, to analyze the convection heat flow, several experiments were performed with the upper plate being the cold plate (see below). The tests were repeated three times for each material and temperature. The standard deviation of the measurements in each sample was of 5%.

Extinction Coefficient

To measure the spectral transmittance, a Fourier transform infrared spectrometer (FTIR) was used, (model Bruker Tensor 27 with DLATGS deuterated L- α -alanine doped with tryglycine sulphate detector). Taking into account experimental results concerning noise, signal intensity, and time required for spectra acquisition, the following conditions were selected: Spectral resolution: 2 cm^{-1} , measured time: 8 scan (accumulations), aperture setting: 6 mm, phase resolution: 8, correction noise: 25 points. The backgrounds were registered to eliminate H_2O and CO_2 contribution.

Transmittance was taken for circular samples of thickness between 1.0 and 4.0 mm, in the wave number infrared region ($4000\text{--}400 \text{ cm}^{-1}$). For these wave numbers there are a substantial radiant energy emitted, as given by the Planck's distribution.

The spectral extinction coefficients K_λ were obtained using Beer's Law.^{16,20}

$$I_\lambda = I_{\lambda 0} e^{-K_\lambda L} \quad (7)$$

where I_λ is the intensity of the incident beam, $I_{\lambda 0}$ is the transmitted intensity, and L is the sample thickness.

To apply this equation samples with different thickness were prepared and the transmittance was measured. K_λ was computed by means of a linear regression as a function of the sample thickness (eq 7).

EXPERIMENTAL RESULTS

Table 1 shows the foams density and average cell sizes of the foams under study, density ranged between 23 and 64 kg/m^3 which means porosities in the range of 97–93% and cell sizes between 630 and $3300 \mu\text{m}$, these cell size are much higher than those previously measured in closed-cell crosslinked polyolefin foams.^{8–10}

Figure 1 shows an example of the microstructure of a typical open-cell polyolefin foam, it is interesting to compare this micrograph with those of conventional foams of similar densities, as an open-cell flexible PU foam produced by free rising and a closed-polyolefin foam produced with the compression molding technology.

The closed-cell foam presents a structure built from polyhedral cells [Fig. 1(b)], being the cells separated by a solid face (cell wall) and the

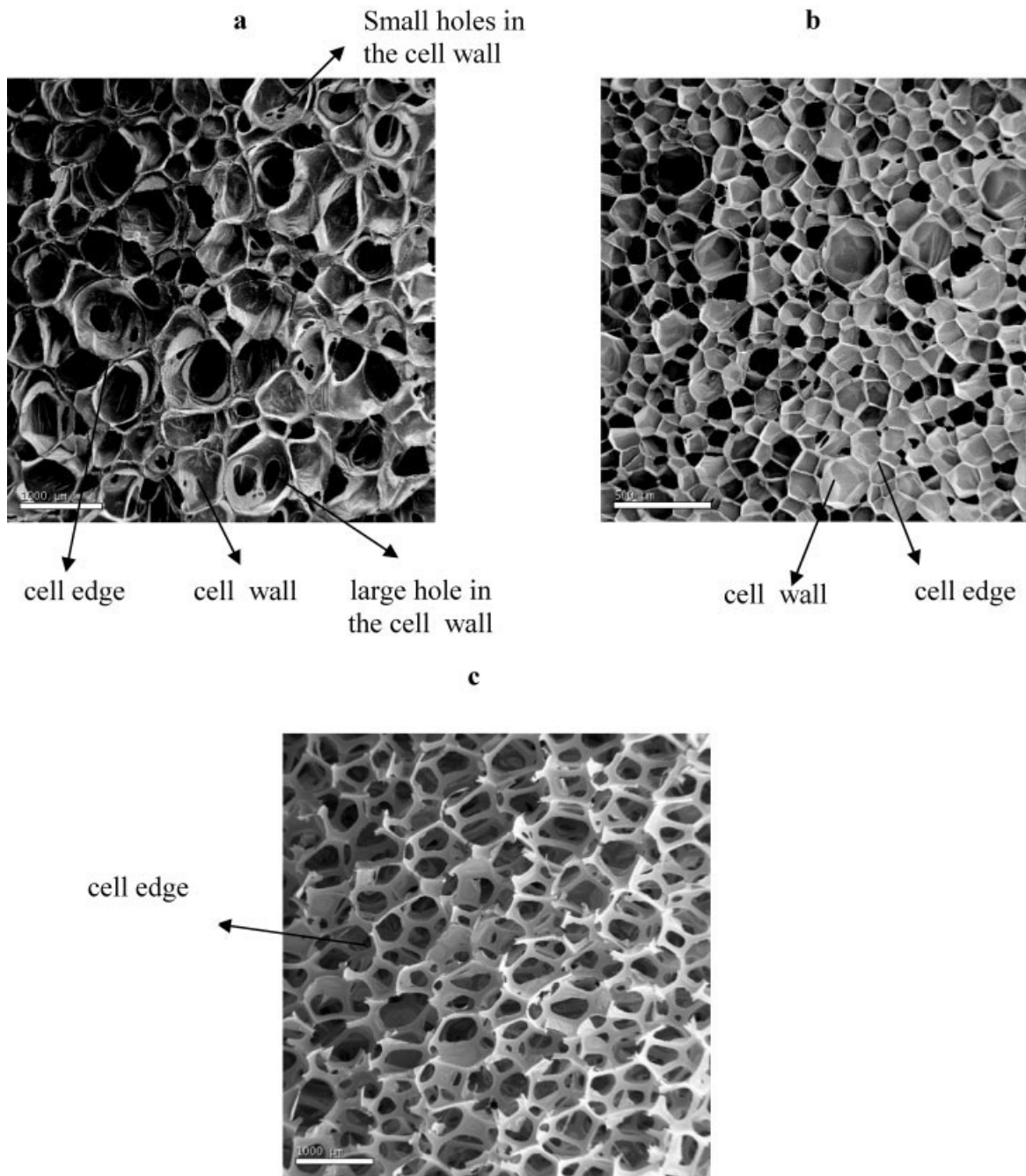


Figure 1. Typical cellular structure of (a) an open-cell crosslinked polyolefin foam, (b) a closed-cell crosslinked polyolefin foam, (c) an open-cell polyurethane foam.

edges are located in the intersections of several cell walls. In the open-cell foam [Fig. 1(a)] the elements of cellular structure are similar, there are also edges and faces, however, most of the cell walls present holes, which can be large (of a similar size to the cell wall size) or very small. These holes allow the gas being in a continuous phase, and therefore this phase would have

some degree of mobility through the foam. From this point of view, these materials can be considered open-cell foams. In fact, the open-cell porosity of all the analyzed materials was 100% (values measured by air picnometry). It is interesting to point out that this kind of cellular structure is clearly different to the typical structure of an open-cell flexible PU foam [Fig. 1(c)],

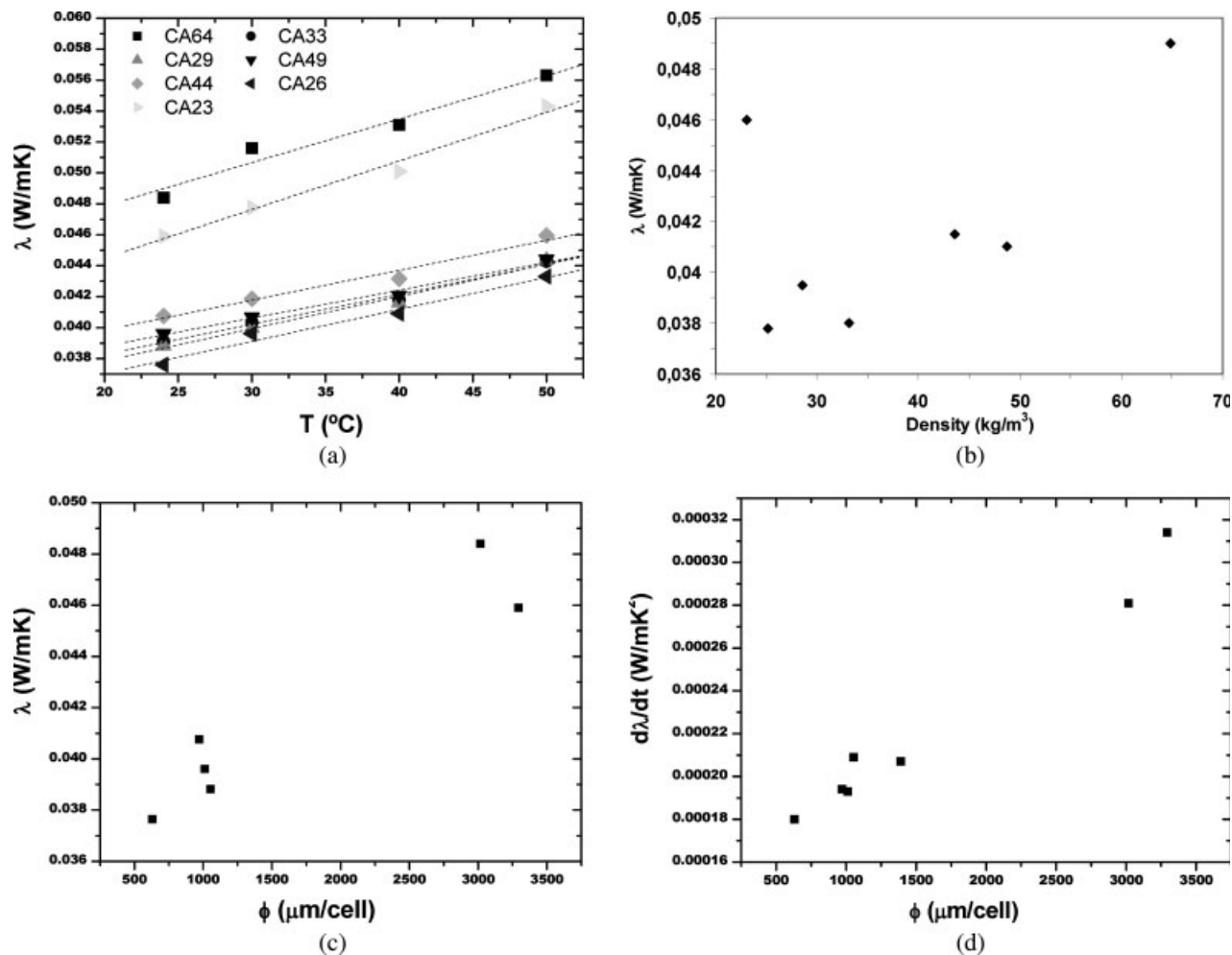


Figure 2. (a) Experimental thermal conductivity (λ) as a function of temperature (T), (b) Thermal conductivity at 24 °C as a function of the foam density, (c) Thermal conductivity as a function of cell size, (d) Slope of the curve thermal conductivity versus temperature as a function of cell size.

for these materials the cellular structure is built from edges, i.e., there is no cell faces including holes.

From the previous description it seems that the structure of the materials under study has several characteristics of the closed-cell material (presence of faces in the cells) and several other of the open-cell material (the gas phase is continuous). In fact the values for f_s were between 0.5 and 0.6 (Table 1), value in between that for the closed-cell polyolefin foams (around 0.2),^{8–10} and that for the open-cell PU ($f_s \approx 1$)

Figure 2(a) shows the experimental thermal conductivity values as a function of temperature. It is clearly observed that conductivity increases linearly with temperature, result that has been also found for closed-cell polyolefin

foams.⁸ A dependence between thermal conductivity and density at fixed temperature was not found [Fig. 2(b)]. However, a clear trend of thermal conductivity and slope of the thermal conductivity versus temperature curve with cell size was detected [Fig. 2(c,d)]. Both parameters increase when the cell size increases. These results indicate that in the range of densities studied the main structural characteristic controlling the foam thermal conductivity is the cell size.

Figure 3 shows a comparative of the thermal conductivity values at 24 °C for these materials, and those previously published^{8,33} for closed-cell foams of similar densities and base polymer (two of the foams were produced from LDPE and the other two from EVA) and produced by

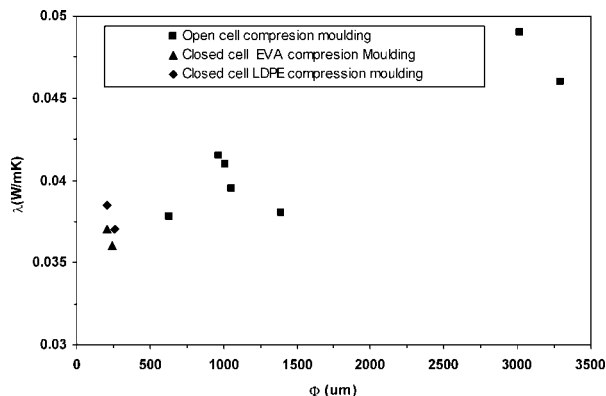


Figure 3. Comparative thermal conductivity values for open-cell foams and closed-cell foams produced by compression molding. Data for the closed-cell foams were taken from refs. 8 and 33.

compression molding. The closed-cell foams analyzed in the cited references had a much smaller cell size in the range of 200–250 μm . It can be observed that, in a general view of the figure, the conductivity of the closed-cell foams is slightly smaller. In fact, the mean value for the four closed foams included in the figure was 0.037 W/mK being the average value for the open-cell materials of this article 0.041 W/mK (a 10% of difference). However, the previous difference is clearly smaller when the open-cell foams of low-cell size are analyzed. For several materials the conductivity of closed-cell and open-cell foams at 24 $^{\circ}\text{C}$ was very similar, which is an unexpected result because in the open-cell materials a higher contribution of convection and radiation should be expected.

To understand the experimental results, an analysis of the heat conduction mechanism using the equations given in “Theoretical Background” section is performed in the following sections.

Convection

The previously explained results were obtained in an experimental setup in which the superior plate was selected as hot plate and the bottom plate was selected as cold plate. In this configuration, the convective currents can not take place. In another collection of experiments the experimental setup was changed selecting the bottom plate as hot face and the upper plate as the cold one. This configuration contributes to activate the convective currents.

The values of thermal conductivity in the temperature range under study and in both kinds of experimental setups were compared being the differences lower than a 1%. Therefore, it was concluded that convective currents are negligible for the open-cell foams under study. This fact is an interesting finding because it indicates that the presence of holes in the cell faces of the cells is not enough to allow the activation of the convective currents.

To compare this experimental fact with theoretical arguments, the Grashof’s number was computed for two extreme assumptions using eq 3.

In a first calculation, it is assumed that all the cells are connected and that the gas mobility between cells is high, under this situation the cell size can be approximated by the sheet thickness (it is equivalent to suppose that all gas is contained in just one cell) being the temperature difference across one cell equal to the temperature gradient. Then using the following values for the parameters of eq 3: $g = 9.81 \text{ m/s}^2$, $\Delta T_c = 303.15$, $\phi = 10 \text{ mm}$, $\rho_{\text{air}} = 1.15 \text{ kg/m}^3$, $\beta = 3.39 \times 10^{-3} \text{ K}^{-1}$, $\eta = 1.86 \times 10^{-5} \text{ Ns/m}^2$ Grashof number results to be 36,000, i.e. much higher than the limiting value to activate the convection mechanisms.

In a second calculation it is supposed that the connection between cells is “weak”, i.e. the gas mobility between the cells is small. Then, using a value of the cell diameter of 1.6 mm (average value for the analyzed foams) and a temperature gradient across one cell of 3 $^{\circ}\text{C}$ ($\Delta T_c = 276.15$) the Grashof number results 136, smaller than the critical value to activate convection.

As convection is negligible for the materials, the second calculation is closer to the real samples behavior. Therefore, the results seems to point out that for the cellular structure of the analyzed materials, in spite of having a connected gas phase, it is necessary a significant driving force (not reached in the thermal experiments described in this article) to activate the gas movement.

Conduction Through the Gas and Solid Phases

The first term eq 2 is the contribution of the gas. The gas in the cells is air, because of the open-cell structure. The thermal conductivity of air at atmospheric pressure and at the temperatures of interest was selected. The second term

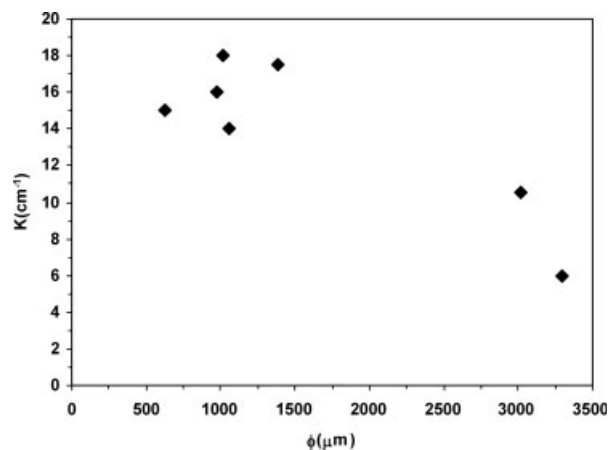


Figure 4. Rosseland extinction coefficient versus cell size.

in eq 3 is the contribution of the solid phase, the thermal conductivity of the solid material comprising the cell walls measured at 24 °C in a solid sheet of similar composition to that of the analyzed foams was used to compute this contribution. The measured value was 0.45 W/mK that was almost independent on the temperature; a variation of 3% was measured between 24 and 50 °C. The values of the contribution of these mechanisms will be explained later (Figs. 7 and 8).

Radiation

The measured extinction coefficients are showed in Figure 4, the values of the extinction coefficient were found to decrease as a function of cell size, which is an indication of a higher heat flow by radiation for the foams with bigger cells.

The values of Figure 4 can be compared with those measured for closed-cell foams of similar compositions and densities.¹⁸ The values for these materials ranged between 20 and 30 values higher than those found for the open-cell materials of this article. Two effects can explain these result, the first one is that the closed-cell foams analyzed in the previous article had a significant smaller cell size, (the range of cells sizes was 200–250 μm), the second one is that radiation in open-cell foams should be smaller because of the presence of holes in several cell walls which allow the transmission of the radiation (through the holes in the cell walls) without energetic losses.

To check the importance of the radiation mechanism in the whole conductivity, the samples were wrapped in an aluminum foil (to reduce radiation) measuring their thermal conductivity (Fig. 5). A significant reduction of the conductivity was found. For foams with high cell sizes (CA64 and CA23) the reduction of the total conductivity was 10%, for foams with lower cell sizes (CA26) the reduction was smaller a 6%. The addition of the aluminum foil has the effect of reducing the heat flow by radiation, this effect is more significant for the foams in which radiation has a bigger effect, i.e. the foams with bigger cells.

PREDICTION OF THE THERMAL CONDUCTIVITY

The model used to compute the thermal conductivity is a combination of the Glicksman model and Rosseland equation (see “Theoretical Background” section), being the convection mechanism neglected.

$$\lambda_T = \kappa_g \Phi_g + \frac{1}{3} (1 - \Phi_g) (1 - f_s) \kappa_s + \frac{16\sigma_B T_m^3}{3K_R} \quad (8)$$

In Figure 6 it is possible to observe a good correlation between experimental data and theoretical predictions, being the differences smaller than 10%. Therefore, the equations used to compute the conductivity, originally developed for closed-cell materials, can also be applied for the open-cell foams of this investigation.

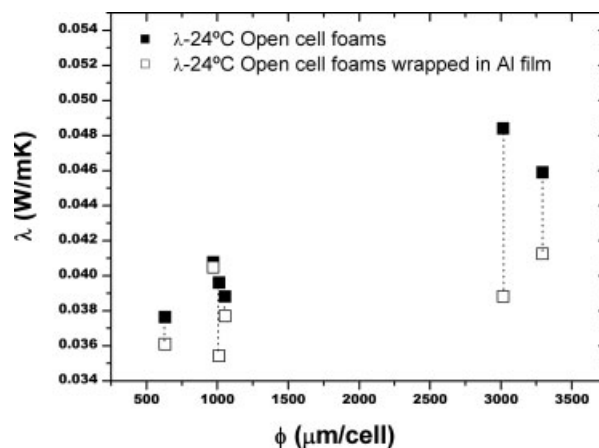


Figure 5. Effect of cell size on the thermal conductivity. Results for foams wrapped in aluminum films.

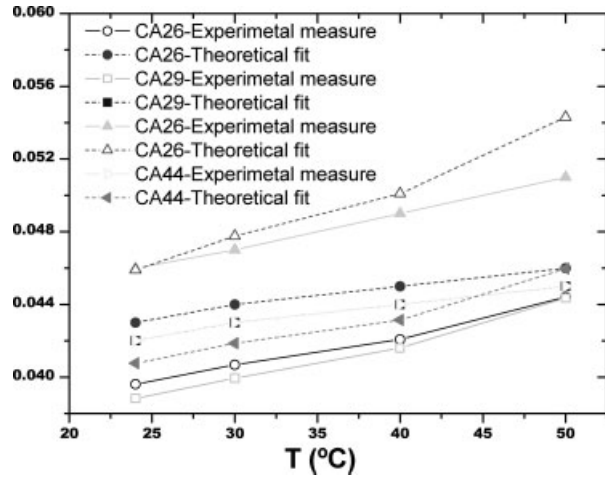


Figure 6. Thermal conductivity (λ) as a function of temperature (T). Experimental and theoretical values for several samples.

The analysis of each contribution to the whole conductivity at 24 °C for all the foams is performed in Figure 7. As it can be observed the contribution of the gas is almost constant in the density range under study, being the polymer contribution slightly higher for the high density foams. The most interesting aspect in this figure is that the experimental curve follows a similar trend than that of the radiation contribution, which seems to indicate that the main differences between the foams is because of a different importance of the radiative contribution in each foam. Furthermore, as radiation is directly controlled by cell size, it can be concluded that the conductivity of the analyzed foams should be mainly controlled by cell size, which is in agree-

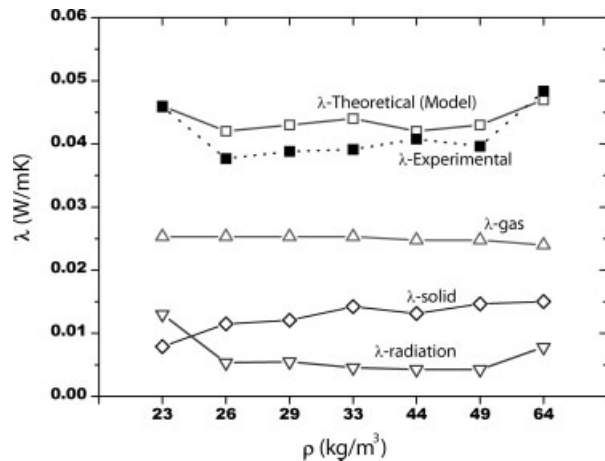


Figure 7. Contribution of each heat transfer mechanism compared with the experimental results.

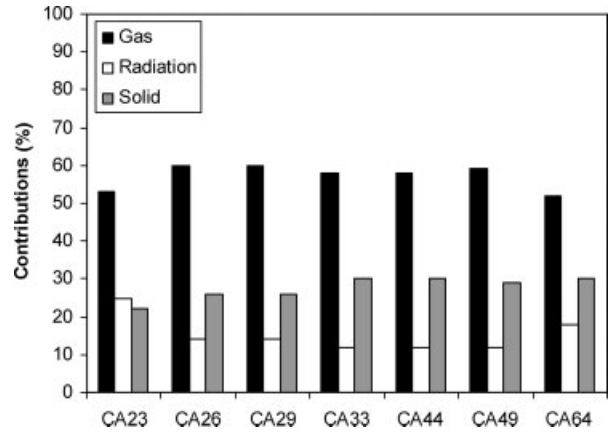


Figure 8. Heat transfer contributions for each mechanism.

ment with the results obtained in the experimental section [Fig. 2(c)]. Therefore, increasing cell size increases conductivity and the slope of the conductivity versus temperature curve; however changes in density does not affect the foams conductivity.

From the previous data it is possible to quantify the weight of each heat transfer mechanism (Fig. 8). The gas conduction accounts for ~56% of the conductivity. Solid conduction accounts for 28% and radiation for approximately a 16%. All these values are similar to those found for closed-cell foams of similar compositions.⁸⁻¹⁰

CONCLUSIONS

The cellular structure of open-cell crosslinked polyolefin foams produced by compression molding is characterized by the presence of cell walls, cell edges, and holes in the cell faces, which permits the gas connectivity. This kind of cellular structure is very interesting from the physical point of view because it produces unexpected results with respect to thermal conductivity of the foams.

It has been confirmed that, in spite of the interconnected cells, the convection mechanism does not play an important role. Moreover, the presence of the cell walls reduces, in comparison to open-cell materials without cell walls radiation. Because of these facts the thermal conductivity of the foams under study was found to be only slightly higher than that of closed-cell foams of similar densities and compositions.

A second interesting information is the increase of the overall conductivity with cell size; this is the most important structural characteristic which controls the foam conductivity in the range of densities under study, and it is also a result typical in closed-cell materials.

The production of the same type of foams but with smaller cells would result in materials with excellent capabilities as thermal insulators (comparable to that of closed-cell foams) keeping at the same time the characteristics given by an interconnected cellular structure, i.e., good acoustic absorption and excellent recovery after creep.

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REFERENCES AND NOTES

- Glicksman, L. R. In *Low Density Cellular Plastics: Physical Basis of Behaviour*; Hilyard, N. C.; Cunningham A., Eds.; Chapman and Hall: UK, 1994, Chapter 5.
- Leach, A. G. *J Phys D: Appl Phys* 1993, 26, 733–742.
- Colishaw, P. G.; Evans, J. R. G. *J Mater Sci* 1994, 29, 486–499.
- Gibson, L.; Ashby, M. *Cellular Solids: Structure and Properties*; Pergamon Press: Oxford, 1998; Chapter 7.
- Shuetz, M.; Glicksman, L. *J Cell Plast* 1984, 20, 114–121.
- Cunningham, A.; Sparrow, D. *Cell Polym* 1986, 5, 327–342.
- Doermann, D.; Sacadur, J. *J Heat Transfer* 1996, 118, 88–93.
- Almanza, O.; Arcos y Rábago, L. O.; Martínez-Díez, J. A.; Rodríguez-Pérez, M. A.; De Saja, J. A. *J Cell Plast* 2001, 37, 21–42.
- Almanza, O.; Rodríguez-Pérez, M. A.; De Saja, J. A. *Cell Polym* 1999, 18, 385–401.
- Almanza, O.; Rodríguez-Pérez, M. A.; De Saja, J. A. *J Polym Sci Part B: Polym Phys* 2000, 38, 993–1004.
- Russel, H. *J Am Ceram Soc* 1935, 18, 1–5.
- Glicksman, L.; Shuetz, M.; Sinofsky, M. *Int J Heat Mass Transfer* 1987, 30, 187–197.
- Ball, G. *J Cell Plast* 1970, 66, 66–78.
- Williams, R.; Aldao, S. *Polym Eng Sci* 1983, 23, 293–298.
- Kuhn, J.; Ebert, H.; Arduini-Schuster, M.; Büttner, D.; Fricke, J. *Int J Heat Mass Transfer* 1992, 35, 1795–1801.
- Tseng, C.; Kuo, K. *J Quant Spectrosc Radiat Transfer* 2002, 72, 349–359.
- Baillis, D.; Sacadura, J. *J Quant Spectrosc Radiat Transfer* 2000, 67, 327–363.
- Campo-Arnaiz, R.; Rodríguez-Pérez, M. A.; De Saja, J. A. *J Polym Sci Part B: Polym Phys* 2005, 43, 1608–1617.
- Placido, E.; Arduini-Schuster, M.; Kuhn, J. *Infrared Phys Technol* 2005, 46, 219–231.
- Wu, J.; Sung, W.; Chu, H. *Int J Heat Mass Transfer* 1999, 42, 2211–2217.
- Park, C. P. In *Handbook of Polymeric Foams and Foam Technology*; Klempner, D.; Frisch, K. C., Eds.; Hanser: Munich, 1991; Chapter 9.
- Khemani, K. C. In *Polymeric Foams: Science and Technology*; Khemani, K. C., Eds.; ACS Symposium Series: USA, 1991; Chapter 1.
- Eaves, D. E. *Cell Polym* 1988, 7, 297–306.
- Puri, R. R.; Collington, K. T. *Cell Polym* 1988, 7, 57–66.
- Puri, R. R.; Collington, K. T. *Cell Polym* 1988, 7, 219–231.
- Hiroo, I. U.S. Patent 4,877,814, 1989.
- Park, C. P. U.S. Patent 6,541,105, 2003.
- Akitaka, S.; Aizawa, T. U.S. Patent 4,424,181, 1984.
- Holman, J. P. *Heat Transfer*; McGraw-Hill: New York, 1981.
- Boetes, R.; Hoogendoorn, C. J. *Proc Int Cent Heat Mass Transfer* 1987, 24, 14–20.
- Rodríguez-Pérez, M. A.; Gonzalez-Peña, J. I.; de Saja, J. A. *Eur Polym J* 2007, 43, 4474–4485.
- ASTM D3576. *Annual Book of ASTM Standards*, Vol. 8(02), 1994.
- Arcos y Rábago, L. O. *Thermal and mechanical properties of polyolefin foams produced by compression moulding*, PhD Thesis, Published by University of Valladolid, Spain, 2002.