IMPROVEMENT OF FOAM INSULATION: FINE CELL SIZE AND COMPOSITE/FOAM VACUUM PANELS

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ABSTRACT

Improvements in the thermal performance of closed-cell foam insulations, which are environmentally sound, are sought for building envelopes and appliances. Recent research on foam insulations at a U.S. university has concentrated on the behavior of fine-cell foams and foam/vacuum composite panels.

The morphology of fine-cell foams allows the contributions of solid conduction and radiation to be identified. A means to measure the fraction of solid in the strut is derived from strut cross-sectional areas. Smaller-celled foams blown with R-141b and perfluoropentane show a redistribution of polymer from the struts to the cell walls as size decreases. Predictions of total conductivity from morphology measurements and transmission measurements agree within 11% with measured total conductivities for six small-celled foams. As the cell sizes are reduced, the radiative contribution is found to be reduced by almost 50%. For very small cell sizes, approaching 100 μm, this may be offset by increased solid conductivity due to redistribution of polymers from struts to cell walls.

Inclusion of small evacuated panels in a rigid closed-cell foam matrix should enhance the insulating performance. The panels were encapsulated in a thin glass-sheet barrier to preserve the vacuum. Glass was chosen as the barrier material because it has a relatively low thermal conductivity and it is effectively impermeable to all gases. Low-cost perlite powder was used because a glass permeation barrier allows low pressures to be maintained within the panel. The thermal conductivity of the evacuated perlite is similar to the thermal conductivity of other finer, more expensive powders, such as silica.

Individual powder panels were produced and tested. The thermal conductivity of the individual panel was found to be 0.0062 W/m·K. The composite foam block with embedded vacuum panels achieved an overall thermal conductivity of 0.01656 W/m·K for a 4.2-cm-thick composite block, and the polyurethane foam had a thermal conductivity of 0.024 W/m·K. Numerical analysis has shown that by using low-conductivity foam and more optimum vacuum panel geometries, much lower overall conductivities can be achieved.

INTRODUCTION

Improvements in the performance of thermal insulation for residential and commercial applications have the potential of significantly reducing the total U.S. energy consumption. More than one-third of the energy consumed in this country is in the residential and commercial sectors. Closed-cell foams such as polyurethane and polyisocyanurate foams have the highest insulating values of any conventional insulations available today. Replacement of the chlorofluorocarbon (CFC) blowing agents with new materials that do not deplete the atmospheric ozone will lead to higher overall conductivities due to the higher conductivity of the new blowing agents.

Research has been under way at a U.S. university to develop improved foams and advanced concepts that have a lower conductivity. This paper will review the progress of two projects—fine-cell foams and composite foam/vacuum panels. The emphasis of the research on fine-cell foams is an accurate determination of the foam morphology so that the influence of fine cells on all aspects of thermal performance can be determined. In the case of foam/vacuum panels, small trial panels were fabricated. Their performance was compared with theoretical models, which were then used to predict the performance of larger systems.

VACUUM PANELS ENCAPSULATED IN FOAM

In some applications, such as refrigerators, there is a need for improved insulation performance to meet more stringent energy standards without an increase in the

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insulation thickness. For these applications, investigators have suggested the use of evacuated insulation panels. In theory, such panels should be able to achieve effective conductivities, which are one-third or less than the best closed-cell foam. One likely concept is a powder-filled panel. The powder has adequate compressive strength to support the pressure difference set up by the vacuum. Numerous tests have shown that a fine powder yields low effective conductivity when the gas pressure is reduced to between 1 and 100 Pa. Radiation is suppressed by using opaque reflecting powders. The solid conduction is limited by the contact resistance between the granules. Gas conductivity is minimized when the mean free path of the gas molecules is less than the interstitial distances between the granules. The gas pressure does not have to be reduced to a high vacuum condition for this to be achieved. Data for this will be given later in the paper.

Because the powder has adequate compressive strength, the envelope for evacuated powder-filled panels does not have to be rigid. Its main function is to prevent air from entering the system and defeating the vacuum. Some investigators have proposed thin metal foils for the envelope material. The insulation performance is compromised by the circumferential heat transfer from high-to-low-temperature surfaces. There are serious losses in R-value even when the panel is 60 cm wide (Glicksman 1991).

Other investigators have used multilayer polymer barriers as the envelope material. Early test results indicated that the insulation performance tends to deteriorate with age due to the entry of air into the system. McElroy (1990) measured a substantial performance degradation after three to five years. Recent work has been carried out on more impermeable polymer films. However, they do admit some air over time. The panels require a fine powder that does not degrade in performance until a high internal gas pressure is reached. This powder has a corresponding cost penalty for the insulation.

In the vacuum insulation research program at the university, the use of glass or ceramic envelope materials has been explored. In this application, the glass has a low permeability to all atmospheric gases. Measurements by Norton on silica glass were extrapolated (Solomou 1993) to a permeability that is 80 orders of magnitude less than the permeability of polymer films. Glass also has a moderate conductivity, minimizing circumferential heat transfer in the vacuum barrier. These insulated panels can be made into small bricks or tiles, which, if closely spaced in a foam block, will form the insulated wall. If one of the panels is damaged, the overall wall performance will not unduly suffer.

Because the glass envelopes are impermeable, the vacuum conditions will be maintained at a constant level over the life of the panel, and a less expensive, coarser powder can be used. One possible application is a matrix of glass-encapsulated panels surrounded by closed-cell foam. The foam will serve to protect the glass surface and also provide resistance to heat flow between the panels. This combination seems a likely evolution of refrigerator manufacture from the existing wall cavity systems. The system could also be used in building retrofit applications where overall thickness is important.

In this paper the thermal performance of panels alone and panels embedded in foam will be examined. A more detailed description is given in Glicksman and Solomou (1994) and Solomou (1993). To reduce the experimental complications, modest-sized panels were fabricated in the laboratory to confirm the assembly techniques. The results were compared to approximate heat transfer calculations. These calculations then allow prediction of the performance of commercial-sized panels.

Panel Fabrication

Although in theory the procedure is simple, in practice the fabrication of an evacuated powder panel insulation prototype system, incorporating thin glass as the barrier, is challenging. Many iterations were necessary to obtain the optimum parameters for each process required. Early attempts to evacuate and seal the panels at glass-softening temperatures were unsuccessful (Burke 1990; Zammit 1992).

In the present investigation, the panel was made in several steps. Powder was formed in the desired shape and encapsulated in a plastic sheet that could be evacuated. This was a relatively inexpensive film that could maintain the vacuum for the short assembly time. The evacuated powder was then placed in a preformed glass envelope whose shape conformed closely to that of the powder. This was then sealed by a second flat-glass panel using a low-temperature vacuum sealant. In this process, the powder was not exposed to a high temperature level. The powder encapsulated in the plastic sheet could be evacuated using a simple room-temperature process. Any small gaps between the glass and powder were filled by vacuum grease. Thus the glass never was unsupported over any of its surface area.

Two different powders were used in the experiments. Perlite—with an average particle size between 20 μm and 30 μm—was the primary powder used. The size was verified with a scanning electron microscope. The second powder used was a fine precipitated silica. The perlite was preheated to between 533 K and 644 K to remove moisture from the sample. The silica was conditioned at 1273 K for two hours to remove silanol groups, which could cause outgassing.

A stainless steel mold was made for forming the plastic sheet and the glass. The conditioned powder was pressed into the preformed plastic shape (held in the steel mold) to reach a density of about 0.7 g/cm^3. The top flat plastic surface was sealed to the lower plastic

surface by thermal fusing in a vacuum apparatus. Samples were made at different vacuum pressures to determine the effect on the overall conductivity.

The same steel mold used to form the evacuated powder samples was used to form the glass. The mold was coated with boron nitride type E to prevent the glass from sticking to it. Thin microsheet glass was used to form the envelope of the panel. The glass had an average thickness of 0.15 mm; the thickness varied from 0.13 mm to 0.16 mm. This glass was used because it is the only glass sheet easily available with this fine thickness that is necessary to limit circumferential heat transfer.

Hot glass was vacuum formed in the steel mold. After the glass cooled, the evacuated powder-plastic element was placed into the glass mold. Any small gaps were filled with vacuum grease. A second flat sheet of glass was attached to the bottom sheet. The two sheets were sealed along a 2-mm to 3-mm-wide flange using torr seal. This sealant is used to maintain a vacuum of 1.3×10^{-7} N/m^2 in commercial applications for long times.

The glass specimens were embedded in precut polyurethane foam boards, and the foam conductivity was measured to be 0.024 W/m·K. In the large built-up matrices, space directly around the panels was filled with a spray foam with a measured conductivity of 0.0325 W/m·K.

MEASUREMENTS

The individual plastic-encapsulated powder was tested two ways before it was enclosed in glass. The panels were immersed in a dye solution. Any holes or gaps in the sealing resulted in visible dye penetration of the sample. The samples were then placed in the vacuum chamber. As the pressure was lowered, a slight bulging of the side walls indicated the approximate pressure level within the sample.

The thermal conductivity of the individual panels was measured with an Anacon 88. Note that this device has heated guard sections so the added heat transfer due to circumferential heat transfer around the edges of the panel cannot be determined.

Several individual panels plus the larger test matrices were tested in a heat flowmeter apparatus with a larger metered section (0.3 m by 0.9 m). Both test machines were calibrated with standard reference materials 1449 and 1450b during the test period. They were found to yield conductivity values within 2% of the standard materials. However, uncertainties for lower conductivity materials are expected to be higher.

RESULTS

Measurements were made for the plastic-encapsulated panels subsequent to the final panel assembly to determine the influence of pressure level, preheat temperature, and powder properties. The perlite-packed panels reached a value between .0062 and .0068 W/m·K at pressure below 10 N/m^2, while the silica had a conductivity of .0056 W/m·K. Figure 1 shows a comparison of the present results for perlite conductivity vs. pressure along with earlier results by McElroy and coworkers. The agreement between the two sets of measurements is close, as

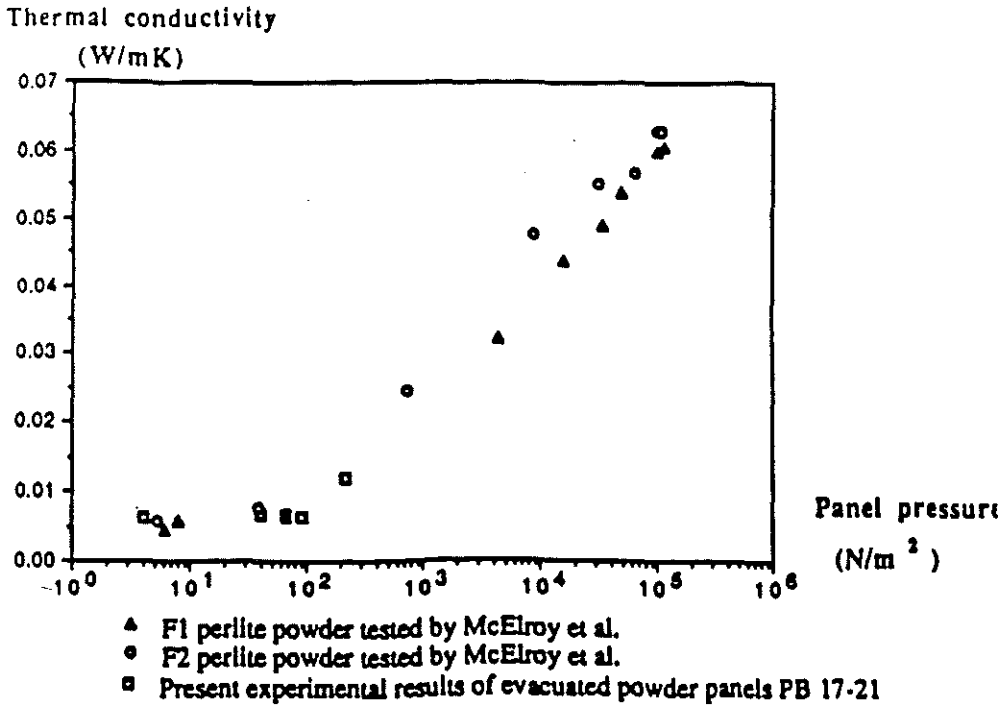

Figure 1 Variation of thermal conductivity with internal panel pressure.

seen in Figure 1. The results indicate the importance of keeping the panel pressure between 10 and 100 N/m^2.

Two of the glass-encapsulated panels were tested individually in the large heatflow meter apparatus. One panel had vacuum grease between plastic and glass, while the other had air in the space. In this case the panel was surrounded, top and bottom, by foam to protect the glass from damage. The overall dimensions were 6.2 cm thick and 26 cm wide. After excluding the effects of foam, a one-dimensional heat transfer model was used, adding in series the thermal resistance of the evacuated powder panel (thickness 1.4 cm), the glass barrier (thermal conductivity 1.4 W/m·K), and the vacuum grease or air layer (thermal conductivity 0.209 W/m·K and 0.02624 W/m·K, respectively). The thermal conductivities of the composite evacuated powder panels encapsulated in glass were calculated. The thermal conductivity of the specimen encapsulated in thin glass, with vacuum grease in the gap between plastic and glass, was found to be 0.0075 W/m·K, whereas the thermal conductivity of the specimen that had atmospheric air in the gap between plastic and glass was 0.0073 W/m·K. These values show that the glass barrier and vacuum grease or an air layer may increase the thermal conductivity values by about 15%. They also demonstrate that there is only a small difference in thermal conductivity values resulting from the use of vacuum grease rather than air, which was only used in the initial specimens.

After each individual plastic-enclosed evacuated powder panel was encapsulated in glass, these composite panels were arranged in matrices. The specimens of matrix C (PB 30-33) (Table 1), containing vacuum grease between the plastic and glass layers, were arranged on different horizontal levels. This arrangement was necessary to minimize the gap between individual glass-encapsulated evacuated powder panels, which subsequently would have to be filled with a foam of higher thermal conductivity. Therefore, to achieve as low an overall matrix thermal conductivity as possible, the individual panels were arranged as shown in Figure 2, which allowed reduction of the gap between them. The specimen flanges were narrow, 1.5 cm, which allowed a compact panel arrangement. The thickness of the matrix was approximately 4.2 cm. Polyurethane board foam with a density of 0.045 g/cm^3, a thermal conductivity of 0.0245 W/m·K, and an average cell size of 0.3 mm was used to protect the panels on each side and top and bottom. The panels were inserted in place with precut foam sheets. Spray foam was used only in the gaps between the individual panels so its contribution to the overall thermal conductivity of the matrix would be minimized. The thermal conductivity of the foam spray was measured as 0.0325 W/m·K. Therefore, polyurethane board foam was preferable because it has a much lower thermal conductivity. The cross-sectional area ratio of evacuated powder panels to foam packaging was found to be 6:1. These

TABLE 1 **Thermal Conductivity Measurements for Plastic-Enclosed Evacuated Powder Panels. Specimens Used in Matrix C.**

Specimen	Powder	Pre-Heated Temperature K	Packing Pressure MN/m^2	Vacuum Pressure N/m^2	Conductivity W/m·K
PB30	Perlite	699	1.379	8.6645	0.0062
PB31	Perlite	589	1.03425	5.332	0.0065
PB32	Perlite	644	1.03425	13.33	0.0066
PB33	Perlite	589	1.03425	26.26	0.0066

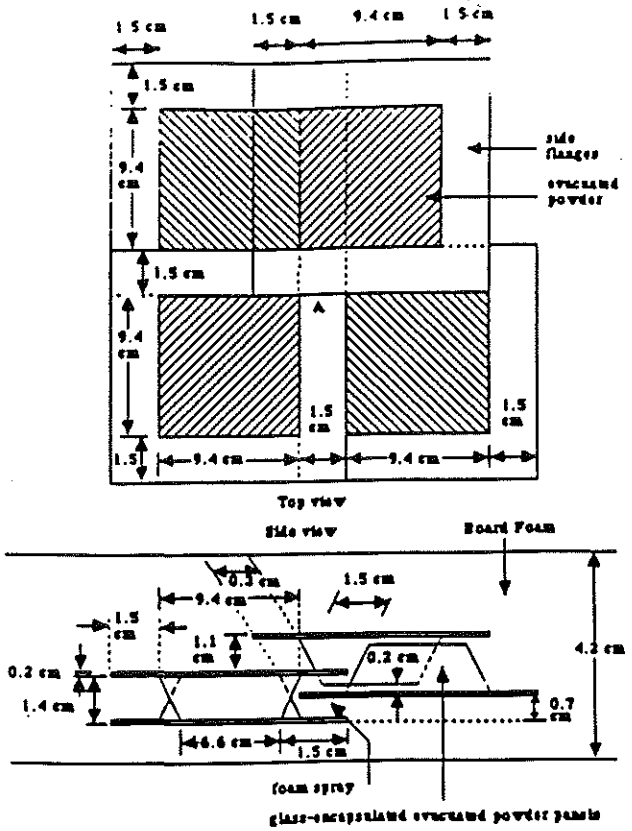

Figure 2 Arrangement of individual glass-encapsulated powder panels in matrix C.

matrices were tested on the device with a larger metered section. Thermal testing of the matrix yielded a thermal conductivity of 0.0166 W/m·K.

The effective conductivity of the panels was calculated modeling each panel as a flat two-dimensional axisymmetric cylinder (Glicksman 1991). The top and bottom of the cylinder had the same surface area as the rectangular panel face. The longitudinal conduction along the face of the glass is explicitly included along with one-dimensional conduction through the powder. The heat transfer through the panel cross section is taken to be in parallel with the heat transfer through the foam between the panels.

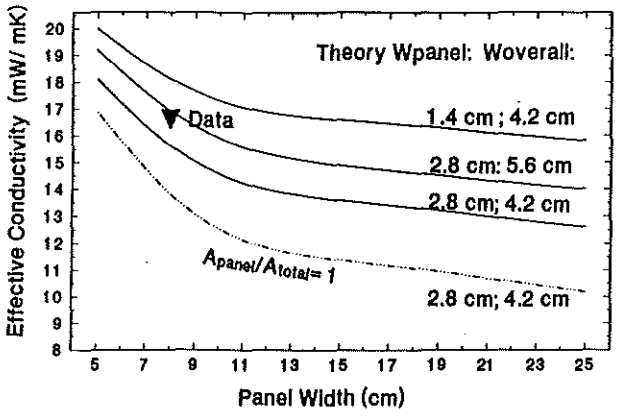

Figure 3 *Effective conductivity panel width. A_{panel}/A_{total} = 5/6 (except bottom curve), k_{powder}: 0.0065 W/m·K, k_{foam}: 0.0245 W/m·K.*

Figure 3 shows a comparison of the data for panel C vs. the approximate calculation of the effective conductivity. The top theoretical curve should correspond to panel C; the data agrees with the model within 9%. As the panel width is increased, the powder thickness increased, the ratio of powder cross-sectional area to total panel area increased, and the effective conductivity fell. Using a foam of lower conductivity 0.20 W/m·K around the panels also will reduce the conductivity values to less than 0.01 W/m·K.

FINE-CELL FOAMS

Closed-cell polyurethane foam is used extensively in the appliance and roofing industry as a thermal insulation because of its low thermal conductivity compared to other conventional insulating materials.

It has long been recognized empirically that the foam morphology has an important influence on the foam conductivity, e.g., at the same overall density, finer cell foams usually exhibit lower overall conductivity. Over the years investigators have attempted to quantify these influences. McIntire and Kennedy (1948) postulated that the overall heat transfer could be expressed by superposition of each heat transfer mechanism taken separately. Russell (1935) developed an expression for the combined effects of gas and solid conduction as a function of the volume fraction of cells in the foam. Reitz et al. (1984) found that in polyurethane foams with typical cell sizes approximately 80% of the polymer was in the struts formed at the junction of the cell walls. Cunningham and Sparrow (1986) derived the contribution of radiation to overall heat transfer from experiments with foams of different cell sizes. Glicksman et al. (1990) developed a simple model for radiation as a function of cell size, which agreed with experimental data for foam with moderate-sized cells.

In the present work, several new techniques to determine the morphology will be presented. These will permit the determination of the percent of polymers in struts for fine-cell foams and establish the distribution of cell sizes for isotropic and anisotropic cell geometries. These morphology characteristics will be related to the heat transfer parameters.

There are three modes of heat transfer in closed-cell polyurethane foams. One mode is conduction across the gases trapped in the foam cells. The second is conduction through the solid polymer surrounding the trapped gas, the cell walls, and strut-like members at the intersection of cell walls. There also is radiation across the foam.

Except in cases where low-emissivity boundaries are used, past work by Glicksman et al. (1987) has shown that ignoring coupling between the heat transfer components provides an accurate description of heat transfer. That is, each heat transfer component can be considered separately, and simply added to account for the total conductivity across the foam.

$$k_{foam} = k_{solid} + k_{gas} + k_{radiation} \tag{1}$$

Radiative transfer reduces to a diffusion process in optically thick material like polyurethane foam. For a one-dimensional case where absorption is more important than scattering, the resulting radiative transfer can be described by the Rosseland equation (Siegel and Howell 1992):

$$k_{radiation} = \frac{16\sigma T^3}{3K_R} \tag{2}$$

where K_R, a measure of the absorbing ability of the material, is the extinction coefficient.

Several measured and statistical quantities could be termed the *cell diameter.* However, in dealing with thermal conductivity, the cell diameter used should be one that relates the physical properties of the foam to the heat transfer process. Torpey and Glicksman (1987) have shown that for radiative conductivity the correct cell diameter measurement is the surface area to volume ratio of the foam. That is, the extinction coefficient, K_R, was shown to be

$$K_R = \frac{4.1}{3.46}\sqrt{f_s\rho_f/\rho_s S_V}\,. \tag{3}$$

The average cell diameter that can be measured from SEM images of foam cells and is still related to this surface to volume ratio is a quantity termed the *mean projected height*. Reitz (1984) has shown that the shape of polyurethane foam cells can be defined accurately by a pentagonal dodecahedron. He shows the mean projected height to be

$$d = \frac{3.46}{S_V}. \tag{4}$$

Note that when the average cell diameters are reduced in size the extinction coefficient increases and the contribution of radiation to the overall foam conductivity decreases.

The solid conductivity component is directly influenced by the void fraction (δ), by the fraction of solid in the strut (f_s), and by the degree of anisotropy of the foam (a/b). An approximate form for the solid contribution (Glicksman 1994) is

$$k_{solid} = \frac{1-\delta}{3} k_{polymer} \left[2(1-f_s)\left(\frac{a}{b}\right)^{\frac{1}{4}} + f_s \sqrt{\frac{a}{b}} \right]. \tag{5}$$

Here $k_{polymer}$ is the conductivity of the solid polyurethane. As the fraction of polymer in the strut, f_s, decreases and more polymer is in the cell walls, the solid contribution increases. For an isotropic foam, when f_s decreases from 1 to 0, the solid contribution doubles.

Two morphology characteristics considered in detail in this work are the distribution of solid polymer between struts and cell walls and the statistical distribution of cell sizes in the foam. The influence of mean cell size on these two characteristics was emphasized in this study because reducing the mean cell size to eliminate radiative conductivity and improve thermal performance is being actively pursued by the foam industry.

For a pentagonal dodecahedron cell geometry, the fraction of solid in the strut can be related to the strut cross section by

$$f_s = \left(\frac{\rho_s}{\rho_f}\right)\left(\frac{8.62}{d^2}\right) A_{strut}. \tag{6}$$

The cross section pictured on a scanning electron microscope (SEM) photograph generally will not be normal to the length of the strut, but may be a cut at some other angle. To account for angular orientations, several strut cross sections are measured for each foam. Thén, the actual cross-sectional area can be related to the average measured cross-sectional area assuming all struts have the same cross section.

The strut is assumed to have equal probability of orientation relative to the plane of the foam sample under examination, thus the area of the strut intersected by the plane, A_{int}, will generally be larger than the true strut cross section.

A number of strut cross sections are measured for a given foam sample. The average intersection area is measured along the maximum intersection area. If all of the struts have the same cross-sectional area then the true cross-sectional area can be determined as (Stewart 1994)

$$A = \bar{A}_{int} \frac{1-\cos\theta_2}{\ln|\sec\theta_2|}, \tag{7}$$

while θ_2 is determined from the maximum intersected area observed,

$$\sec\theta_2 = \frac{A_{max}}{A}. \tag{8}$$

The calculation of foam cell size distribution from SEM or confocal micrographs is not as straightforward as measuring the distributions of diameters on the micrographs. Even if all foam cells are spheres with exactly the same diameters, a random section plane through the foam will cut cells at different distances from the cell center, yielding a distribution of sizes on the micrograph. Adding complexity to the problem is a nonuniform distribution of cell sizes.

The method used in the present study obtains the size distribution from measured section areas. Unlike many others, this method works for cells of nonspherical shapes. Previous work (Reitz 1984) indicates that polyurethane foam cells are best characterized by polyhedral shapes such as the pentagonal dodecahedron. The method used in this work is a new numerical solution of relationships given by Underwood (1970). Previous solutions were developed to minimize numerical calculations, and probably were carried out by hand. Most of the other methods that could handle nonspherical shapes are unwieldy.

The cell sizes are found from the solution of the matrix equation (Stewart 1994):

$$[N_A] = [A]\,[N_V] \tag{9}$$

where

$$A_{ij} = P_{ij} d_j \tag{10}$$

where N_{A_i} is the number of cross sections of diameter d_i that are found on a plane section of the foam, N_{Vj} is the number of three-dimensional cells with true diameter d_j, and P_{ij} is the probability that a section plane will intersect a cell of size d_j to yield a section of diameter d_i.

RESULTS

Six closed-cell foams were provided by a commercial supplier. They range from typical foams in use today to possible fine-cell improvements. The fraction of solid in the strut was, in general, found to decrease as the cell size was reduced (Figure 4). The cell size distributions were found to be modest around the mean value; typical results are shown in Figure 5. For five out of the six

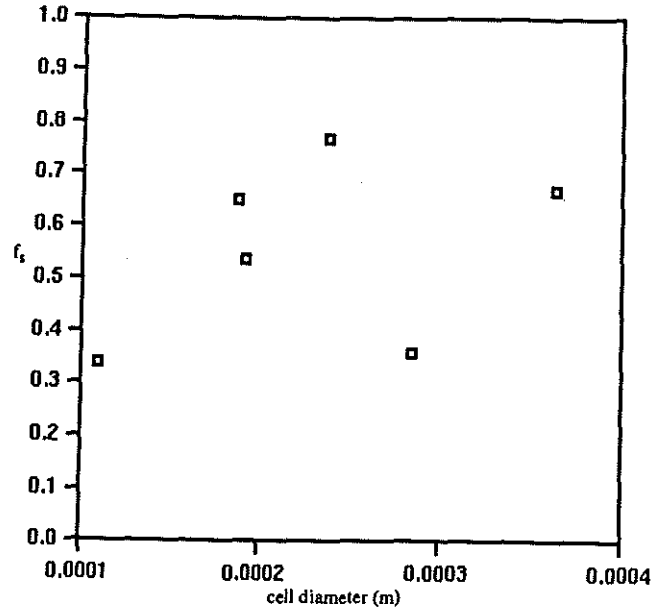

Figure 4 Measured fraction of solid in strut vs. foam cell size.

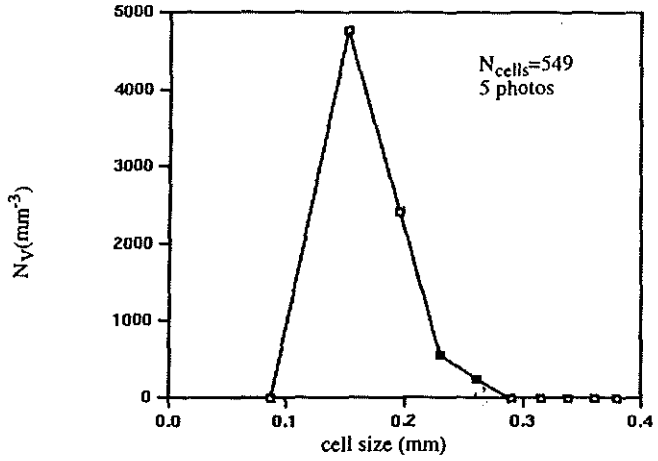

Figure 5 Foam NBE 819/16/2 cell size distribution.

foams the maximum error in radiative conductivity was 11% or less, using the mean cell diameter rather than the true cell size distribution in calculating the extinction coefficient. The overall predicted conductivity, shown in Figure 6, is made up of components predicted from the measured morphology. The overall predicted value agrees closely with the measured conductivity. Note that, in this case, the radiative contribution is reduced by about 50% and it becomes modest as the cell size is reduced, while the solid contribution climbs somewhat. For the foam with the finest cells, the overall value is increased due to the use of a higher conductivity blowing agent.

CONCLUSIONS

A prototype glass-encapsulated powder-filled vacuum panel has been produced. Because the glass

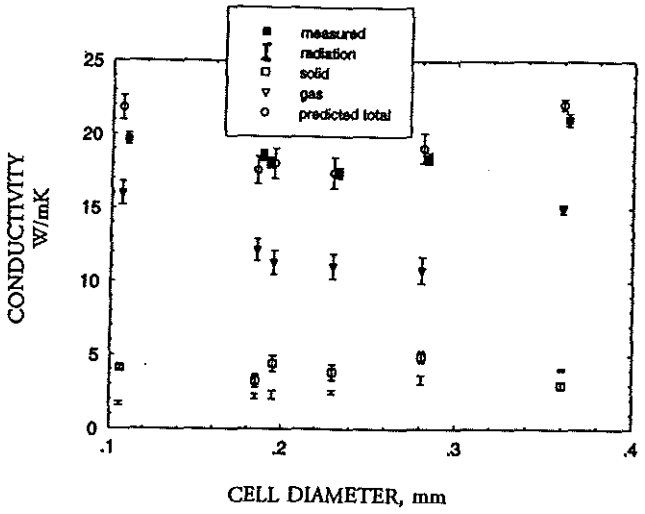

Figure 6 Comparison of total conductivity measured and predicted from morphology measurements. (Note: Uncertainties in gas conductivity, solid conductivity, and radiative conductivity also shown.)

encapsulant has low permeability, an inexpensive powder of moderate-sized perlite can be used in the panel.

Perlite powder exhibits a conductivity between 0.0062 and 0.068 W/m·K at air pressures of less than 10 Pa. When the glass-encapsulated perlite panel is embedded in foam, a relatively high conductivity of 0.0166 W/m·K was measured for the assembly. This value can be significantly reduced to 0.010 W/m·K or less by closer packing of panels, use of panels 25 cm wide, and use of lower conductivity foam to encapsulate them. Future work should be carried out to demonstrate the performance of optimum panel geometries.

A technique to measure the fraction of solid in the struts from SEM photos of strut cross-sectional areas has been developed. The technique is simpler to use than measurements of cell wall thicknesses. Use of the new measurement technique for six small-celled foams indicates a redistribution of solid polymer from the struts to the cells walls as mean cell size decreases for the samples examined.

The total heat transfer predicted from the measured foam morphology agrees closely with the measured conductivity. Fine-cell foams have reduced radiation, while for the particular samples examined the solid conductivity increased.

A means to calculate the cell size distribution from SEM or confocal microscope images of cell section areas also has been developed for both collections of isotropic and anisotropic foam cells. Measurements of foam cell size distributions indicate that, for the foam sample examined, most cells have diameters close to the mean cell diameter.

ACKNOWLEDGMENTS

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NOMENCLATURE

a,b = cell major and minor axes
A = strut cross section
d = cell diameter
f_s = fraction of solid in struts
k_{foam} = overall foam conductivity
k_{gas} = gas contribution to conductivity
$k_{polymer}$ = conductivity of solid polymer
$k_{radiation}$ = radiative contribution to conductivity
k_{solid} = solid contribution to conductivity
K_R = Rosseland mean extinction coefficient
N_A = number of cross sections of diameter d_i
N_V = number of cells of diameter d_j
P = probability
S_V = surface area to volume ratio
T = absolute temperature
θ = spherical coordinate
σ = Stefan-Boltzmann constant
ρ_f = foam density
ρ_s = solid polymer density

Subscripts

i = size of two-dimensional images in cross section
j = actual three-dimensional cell sizes

REFERENCES

Burke, M. 1990. Insulation based on silica powder vacuum-packed in thin glass. Master's thesis. Cambridge: Massachusetts Institute of Technology.

Cunningham, A., and D.J. Sparrow. 1986. Rigid polyurethane foam: What makes it the most effective insulant? *Cellular Polymers* 5: 575-587.

Glicksman, L.R. 1991. Two-dimensional heat transfer effects on vacuum and reflective insulations. *Journal of Thermal Insulation* 14: 281-294.

Glicksman, L.R. 1994. Heat transfer in foams. In *Low Density Cellular Plastics: Physical Basis of Behaviour*, pp. 104-152, N.C. Hillyard and A. Cunnignham, eds. London: Chapman & Hall.

Glicksman, L.R., and N. Solomou. 1994. Development of rigid foam/evacuated powder composite panels for thermal insulation. *SPI: Polyurethanes 1994 Conf. Proceedings.*

Glicksman, L.R., M. Schuetz, and M. Sinofksy. 1987. Radiation heat transfer in foam insulation. *Int. Jour. Heat Mass Transfer* 30(1): 187-197.

Glicksman, L.R., M. Mozgowiec, and M.R. Torpey. 1990. Radiation heat transfer in foam insulation. *Heat Transfer 1990 Proc. 9th Internation Heat Transfer Conf.* 9: 379-384. Washington, D.C.: Hemisphere Pub. Corp.

McElroy, D.L., D.W. Yarbrough, G.L. Copeland, F.J. Weaver, R.S. Graves, T.W. Tong, and H.A. Fine. 1990. Development of advanced thermal insulation for appliances. Technical Report ORNL/CON-159. Oak Ridge, Tenn.: Oak Ridge National Laboratory.

McIntire, O.R., and R.N. Kennedy. 1948. Styrofoam for low temperature insulation. *Chem. Eng. Prog.* 44(9): 727-730.

Reitz, D.W. 1984. A basic study of gas diffusion in foam insulation. Master's thesis. Cambridge: Massachusetts Institute of Technology.

Reitz, D.W., M.A. Schuetz, and L.R. Glicksman. 1984. A basic study of aging of foam insulation. *Journal of Cellular Plastics* 20(1): 104-113.

Russell, H.W. 1935. Principles of heat flow in porous insulators. *J. Amer. Ceramic Society* 18(1): 1-5.

Siegel, R., and J.R. Howell. 1992. *Thermal radiation heat transfer*, 3d ed. Washington, D.C.: Hemisphere Publishing Corp.

Solomou, N. 1993. Development of advanced insulation systems: Evacuated powder panels encapsulated in a thin glass barrier. Master's thesis. Cambridge: Massachusetts Institute of Technology.

Stewart, J. 1994. The influence of morphology on polyurethane foam heat transfer. Master's thesis. Cambridge: Massachusetts Institute of Technology.

Torpey, M.R., and L.R. Glicksman. 1987. The influence of cell size and foam density on the thermal conductivity of foam insulation, pp. 80-84. Aachen, Germany: *Proc. Polyurethane World Congress 1987.*

Underwood, E.E. 1970. *Quantitative stereology.* Reading, Mass.: Addison-Wesley.

Zammit, M. 1992. Development of powder evacuated panel insulation which is encapsulated in a thin glass barrier. Master's thesis. Cambridge: Massachusetts Institute of Technology.