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A Study on Rigid Foam/Evacuated Powder Composite Panels for Thermal Insulation

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The present study investigates the feasibility of a composite panel: a series of individually evacuated panels incapsulated in a rigid closed cell foam matrix. The panels were encapsulated in a thin glass sheet barrier to preserve the vacuum. Glass has been 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 has also been used, because its thermal conductivity is very similar to the thermal conductivity of other finer and more expensive powders, such as silica provided that low pressures are maintained within the panel by using a glass gas permeation barrier. The individual plastic-enclosed evacuated powder panels encapsulated in a thin glass barrier, have been put together in a matrix structure so that even if one individual panel is punctured or damaged, the insulating performance of the entire matrix is not significantly affected. Individual powder panels were produced and tested in this study. 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. The polyurethane foam used above foam block had a thermal conductivity of 0.024 W/m·K. Numerical analysis has indicated that by using low conductivity foam and more optimal vacuum panel geometries, much lower overall conductivities can be achieved.

Key Words : Evacuated Powder Panel Insulation , Polyurethane Foam , Thermal Conductivity, Numerical Analysis.

1. Introduction

Improvements in the performance of thermal insulation for residential and commercial applications have the potential of significantly reducing the total energy consumption. Over one third of the energy consumed in U.S.A. is in the residential and commercial sectors. Closed cell foam such as polyurethane and polyisocyanerate foams have the highest insulating values of any conventional insulations available today. However, inmany applications the conductivity increases with time due to air diffusion into the closed cells. These are well explained by Glicksman and Ostrogorsky (1989). Glicksman and Page (1989) also showed that replacement of the conventional CFC blowing agents with new materials which do not deplete the atmospheric ozone can lead to higher overall conductivities.

In some applications such as refrigerators, there is a need for improved insulation performance to meet more stringent future energy standards without an increase in the 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. Several different evacuated insulation systems have been proposed to be used as flat wall panels for appliances. One version

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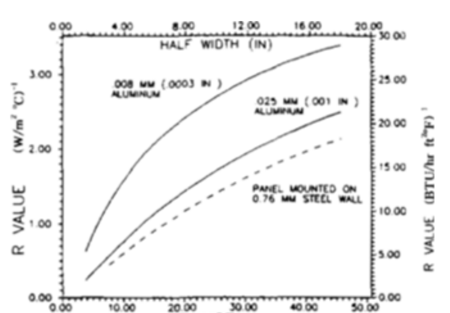


Fig. 1 Overall conductivity of aluminum foil over 2.5 -cm-thick powder with $R=7(W/m^2\ ^{\circ}C)^{-1}$, $40(BTU/hr\ ft^{2\circ}F)^{-1}$.

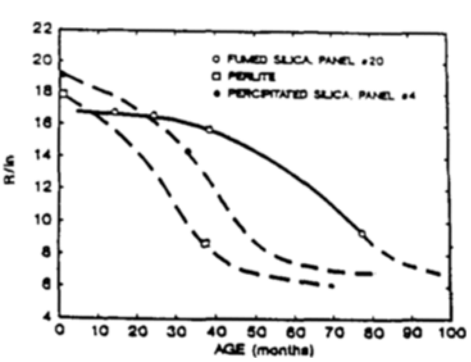


Fig. 2 Thermal Resistance of three polymer encapsulated evacuated powder panels with time.(The unit of R-value per inch arc hr ft² °F/BTU).

consists of two parallel metal walls separating a high vacuum space. In the flat configuration, a substantial thickness is needed for mechanical strength along with spacers to support the walls. The structural requirements lead to unacceptably high conduction heat transfer around the circumference of the panel when it is of modest dimensions, a width of one meter or less. A more 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 can be 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 Fig. 6

Since the powder has adequate compressive strength the envelope for an evacuated powder filled panels does not have to be rigid. Its main function is to prevent air entering the system and defeating consequently the vacuum. Some investigators have proposed thin metal foils for the envelope material. If there are no pinholes or other defects, such an envelope should permit a long lived vacuum. Even when such thin metal sheets are used, they must be joined at the edges to provide a permanent seal. Again the insulation performance is compromised by the circumferential heat transfer from the high to the low temperatures surfaces. Figure 1, taken from Glicksman (1991), shows the decrease in the thermal resistance R value of an evacuated powder covered with .008 mm and .025 mm aluminum foil, respectively. There are serious losses in R value even when the panel is 60 cm wide.

Other investigators have been using multi layer polymer barriers as the envelope material. Early test results indicated that the insulation performance tends to deteriorate with age due to the air entry into the system. Figure 2, taken from McElroy (1984), illustrates the 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 very fine powder which does not degrade in performance until a rather high internal gas pressure is reached. Such a fine powder has a corresponding cost penalty for the insulation.

In the program of vacuum insulation research at the Massachusetts Institute of Technology the use of glass or ceramic envelope materials have been explored. In this application the glass has a low permeability to all atmospheric gases. Solomou (1993) has showed that measurements by Norton on silica glass extrapolates to a perme-

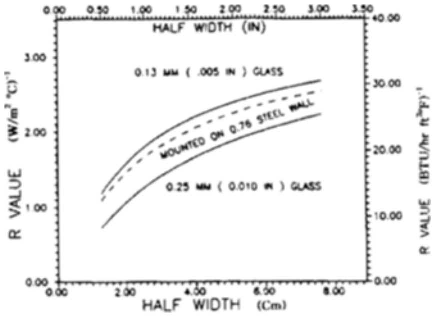


Fig. 3 Overall conductivity of glass film over 2.5-cm-thick powder with 40(BTU/hr ft$^{2\circ}$F)$^{-1}$.

ability which 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 element. Figure 3 illustrates the predicted insulation value as a function of panel width for a powder encapsulated by a thin glass envelope. With this envelope material, a width of 12 to 15 cm is sufficient to minimize thermal edge losses. These insulated panels could be made into small bricks or tiles which would form the insulated wall. In that way if one of the panels was damaged the overall wall performance would not unduly suffer.

Since the glass envelopes are very inpermeable, a less expensive coarser powder can be used since the vacuum conditions will be maintained constant over the life of the panel. One likely 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.

In the present paper, the construction of glass encapsulated insulated panels will be described. The thermal performance of panels alone and panels embedded in foam will be examined. To reduce the experimental complications, rather modest sized panels were fabricated in the laboratory to confirm the assembly techniques. The results will be compared to approximate heat transfer calculations. These calculations will then allow prediction of the performance of commercial sized-panels.

2. Panel Fabrication

Although the procedure is simple, in theory the fabrication of an evacuated powder panel insulation prototype system, incorporating thin glass as the barrier, is very challenging in practice. Many iterations were necessary in order to obtain the optimum parameters for each process required.

Bruke (1990) wrapped a pre-compressed powder brick with thin micro-sheet glass in a vacuum furnace at the temperature slightly above the softening point of glass. Because the micro-sheet is very thin, the powder shape should be the same as that of the glass so as to support it. It was hoped that once soft, the top sheet of glass would sag over the powder and form a seal with the bottom sheet of glass. Although a relatively simple procedure, no samples with any significant vacuum were produced. Proper sealing between the two sheets of glass could not be insured.

Zammit (1992) carried out an alternate fabrication process. One sheet of thin glass was formed in a steel mold to the required shape. Powder was packed into the molded sheet and a second flat sheet of thin glass placed above. The assembly was placed in a vacuum oven evacuated and heated to the glass softening temperature. This technique did allow a sealed envelope to be formed. However, at the glass softening temperature, gases absorbed in the powder were released and they caused the assembly to expand leaving a void under the glass film. To alleviate this expansion, after the glass sheets sealed together at the elevated temperature the pressure in the furnace was raised preventing the void to expand. Unfortunately, the compression of the powder at elevated temperature caused the particles to partially fuse, to substantially increase in the solid conduction.

In the present investigation, the panel was made in several steps. Powder was formed in the desired shape and encapsulated in a plastic sheet which could be evacuated. This was a relatively inexpensive film which could maintain the vac-

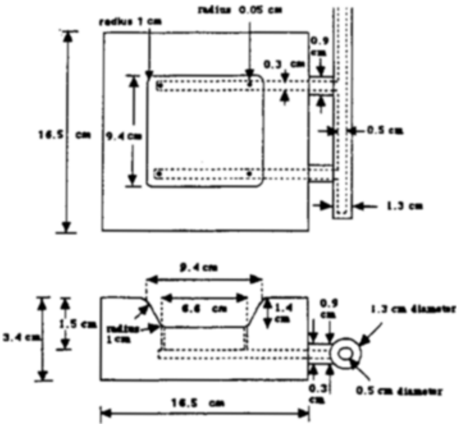


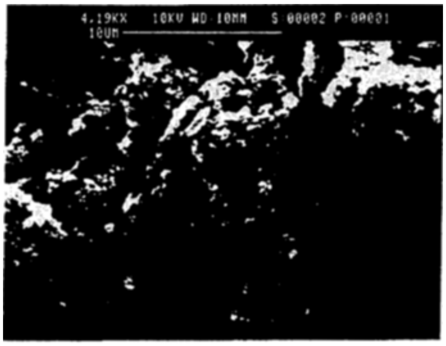
Fig. 4 The stainless steel mold used to form the plastic and glass layers.

uum for a short assembly time. The evacuated powder was then placed in a pre-formed 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 in the plastic 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.

A stainless steel mold was made to be used in forming the plastic and the glass, (see Fig. 4). The mold has holes in the bottom, which allow suction to be applied to draw the material into the mold. Since the plastic tended to shrink after it was withdrawn from the mold a thin spacer was placed on the top edges of the mold. The plastic was clamped between the spacer of an overall thickness of 0.13 mm. It had a middle layer of EVOH covered with Tie which was, in turn, covered with LDPE on both sides. These are well explained by Solomou (1993)

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 by use of a scanning electron microscope. The second powder used was a fine precipitated silica, see Fig. 5.

(a) Perlite



(b) Precipitated silica

Fig. 5 Micro-structure of the powders used in the experiments.

The perlite was pre-heated between 533K and 644K to remove moisture from the sample. The silica was conditioned at 1273K for two hours to remove silanol groups which could cause outgassing.

The conditioned powder was pressed into the preformed plastic, 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 micro sheet glass, manufactured by Corning Glass Works, was used to form the envelope of the panel. The glass had an average thickness of 0.15mm, the thickness varied from 0.13mm to 0.16mm.

This glass was used because it is the only glass sheet easily available with this fine thickness which is necessary to limit circumferential heat transfer. The glass was placed in the mold and covered with a second hollow steel plate weighing 0.7 kg. The glass and molds were heated to 1022K in a furnace. A vacuum pump was used to draw the glass into the mold. The glass and mold were slowly cooled over fifteen hours to avoid thermal stress failure.

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 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 polyurethane foam boards, and the foam conductivity was measured to be 0.024 W/m·K. In the large built up matrices, the space around the panels was filled with a spray foam which had a conductivity of 0.0325 W/m·K.

3. 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, 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 which makes measurements in accordance with ASTM standard C177. Note that this device has heated guard sections so that the added heat transfer due to circumferential heat transfer around the edges of the panel can not be determined.

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

4. Results

Tabel 1 Thermal conductivity measurements for plastic-enclosed evacuated powder panels

Specimen	Powder	Pre-heated Temperature °K	Packing Pressure MN/m^2	Vacuum Pressure N/m^2	Conductivity W/m°K
PB14	Perlite	589	2.0685	39.99	0.0076
PN12	Perlite	None	2.0685	39.99	0.0088
SB1	Silica prec.	644	1.379	33.325	0.0061
SN2	Silica prec.	None	1.379	33.325	0.0074
PB15	Perlite	533	0.6895	6.665	0.0063
SB2	Silica prec.	533	0.6895	6.665	0.0056
PB16	Perlite	589	1.03425	13.33	0.0072
SB3	Silica prec.	589	1.03425	13.33	0.0059
PB17	Perlite	589	1.03425	3.000	0.0065
PB18	Perlite	589	1.03425	39.99	0.0068
PB19	Perlite	589	1.03425	66.65	0.0068
PB20	Perlite	589	1.03425	93.31	0.0066
PB21	Perlite	589	1.03425	213.28	0.0120
PB22	Perlite	505	1.03425	15.996	0.0065
PB23	Perlite	616	1.03425	39.99	0.0071
PB24	Perlite	533	1.72375	13.33	0.0065
PB25	Perlite	566	1.03425	5.332	0.0063
PB26	Perlite	589	1.03425	6.665	0.0065
PB27	Perlite	533	1.03425	3.999	0.0068
PB28	Perlite	422	1.03425	3.999	0.0075
PB29	Perlite	589	1.379	26.66	0.0066
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

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. Table 1 summarizes the test results. The perlite

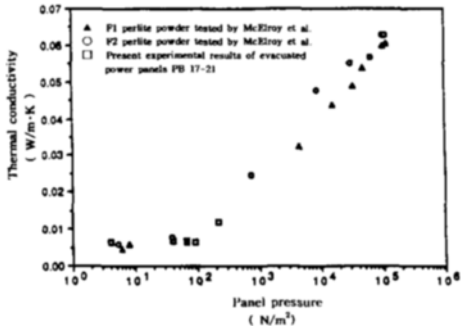


Fig. 6 Variation of thermal conductivity with internal panel pressure.

packed panels reached a value between. .0062 and .0068 W/m·K at pressure below 10N/m² while the silica reached a conductivity of .0056 W/m·K. Fig.6 shows a comparison of the present results for perlite conductivity versus pressure along with earlier results by McElroy et al (1984) The agreement between the two sets of measurements is quite striking. The results indicate the importance of keeping the panel pressure between 10 and 100 N/m².

Two of the glass encapsulated panels were individually tested in the large heat flow meter. One panel had vacuum grease between plastic and glass, 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 as shown in Fig. 7. The overall dimensions were 6.2 cm thick and 26 cm wide. After excluding the effects of foam, using a one-dimensional heat transfer model, 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 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 specimen PB22 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 specimen PB25, which had atmospheric air in the gap between plastic and glass, was 0.0073 W/m·K.

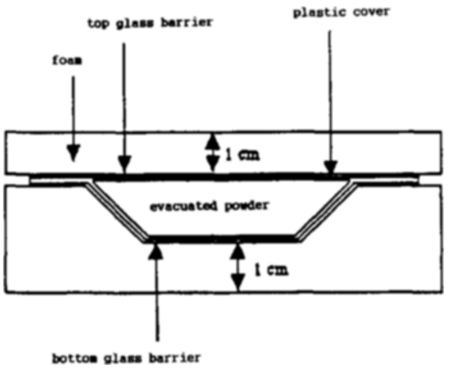


Fig. 7 Test set-up of individual glass-encapsulated, evacuated powder panels.

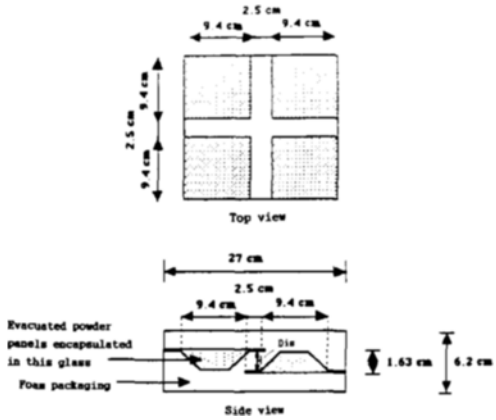


Fig. 8 Arrangement of individual glass-encapsulated evacuated powder panels in matrices.

These values show that the glass barrier and vacuum grease or air layer increase the thermal conductivity values by about 15%. They also demonstrate that there is only a small difference in thermal conductivity values resulting by 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. Matrices A and B (Fig. 8) were made, each containing four of the individual glass-enclosed evacuated powder specimens, which were successful in terms of high thermal resistance. Matrix A contained specimens PB 22–25, with the gap remaining between the plastic layer and glass barrier being covered with vacuum grease. The vacuum grease height estimated both visually and by using the displacement method was found to be 2 mm. Matrix B contained specimens PB 26–29 and the gap between the plastic and the glass was left to be filled with atmospheric air. The glass 0.15mm, whereas the foam packaging has a thermal conductivity of 0.032 W/m·K and a thickness of 2.3 cm on either side of the panel.

These matrices were tested on the device with a larger metered section. The thermal conductivities of the matrices containing the individual evacuated powder panels, encapsulated in a thin glass barrier, were found to be 0.021 W/m·K for panel A and 0.0205 W/m·K for panel B.

The overall matrix thermal conductivity values obtained were much higher than the individual evacuated power panels encapsulated in glass. The reason for this was the poor performance of the foam packaging and a wide spacing between the individual panels. At the level of the panels, less than one half of the overall cross sectional area is occupied by the evacuated panels.

5. Numerical Analysis

A finite element program was written to model the effective conductivity of the panels and to identify the performance improvements which could be obtained by changing the panel and foam geometry. Figure 9 illustrates the geometry of the panels which was modeled. To simplify the mesh requirements, the envelope which is composed of two layers of glass and plastic along with a layer of vacuum grease was modeled by a homogenous equivalent layer. Since the impact of the envelope is primarily to conduct heat along its length, the effective homogenous layer has the same product of conductivity and thickness as the sum of this product for each individual layer. It has been shown that the use of the equivalent layer only causes an inaccuracy of about 0.4 percent.

In this analysis three node triangular elements were used. The resulting matrix equations were solved by a Gaussian elimination method with the banded stiffness matrix method. These are well explained by Noborou (1986). An automatic mesh generator by Noborou (1986) and as post-processor Tecplots developed by Amte Engineering were used to provide the coordinates of the nodal points and mesh drawings. To test the accuracy of the program a comparison was made with the temperature distribution in a rectangular array with a uniform heat generation and a uniform boundary temperature. Using 100 uniform triangular elements gave a numerical result which agreed with the analytic solution within 0.1 percent.

A three dimensional simulation was carried out and compared to the experimental result for configuration in Fig. 8. The numerical result agreed with the experimentally measured value within 0.5 percent as shown on Fig. 11. Because of the relatively long computational time, parametric

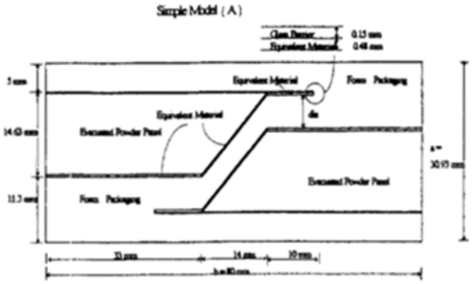


Fig. 9 Simple Model (A) geometry of rigid foam/evacuated powder composite panels with envelope.

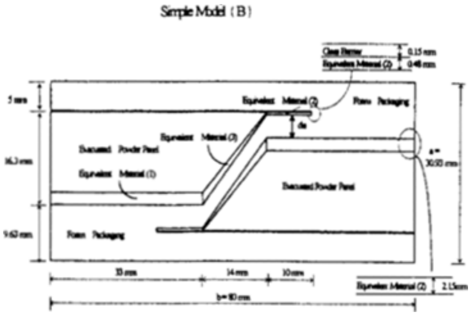


Fig. 10 Simple Model (B) geometry of rigid foam/evacuated powder composite panels with envelope.

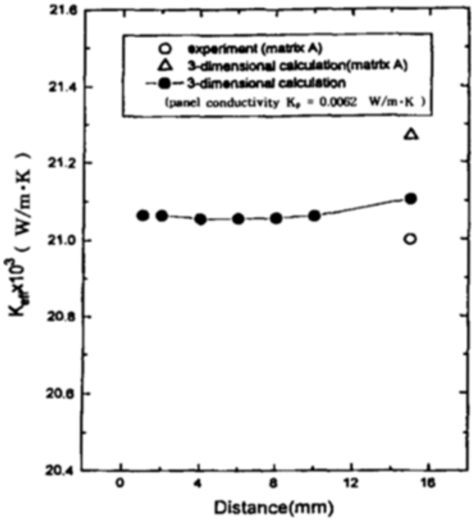


Fig. 11 Effective conductivity of rigid foam/evacuated powder composite panels with respect to distance(three-dimensional calculation domain on figure 8 , aspect ratio (b/a) : 1.919 , using brick element, ● : three-dimensional calculation results in case of fixed panel conductivity (K_{panel} = 0.0062 W/m·K) is used)

studies were carried out for two geometries shown on Fig. 9 and Fig. 10. The former includes a constant thickness layer of vacuum grease around the circumference while the latter has the variant thickness vacuum grease layer.

Figure 12 shows the influence of the aspect ratio and spacing of the panels in the case of Simple Model(A) as shown Fig. 9. For this case the volume fraction of foam and of the evacuated powder are maintained constant in the panel. As the aspect ratio increases the ratio of panel length normal to the applied temperature gradient is increased relative to the panel width parallel to the temperature gradient. It can be seen, as expected, that the aspect ratio has a substantial influence on the effective conductivity. As the aspect ratio increases, the conduction path length along the envelope increase. The separation distance between panels, defined in Fig. 9 and Fig. 10, also influences the effective conductivity. Within the range of distances shown in Fig. 12 the influence is modest compared to the aspect ratio.

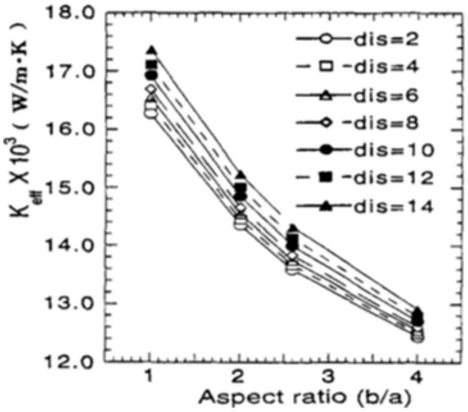


Fig. 12 Effective conductivity of rigid foam/evacuated powder composite panels with respect to aspect ratio for value of distance between evacuated powder panels. Separation distance given in mm.

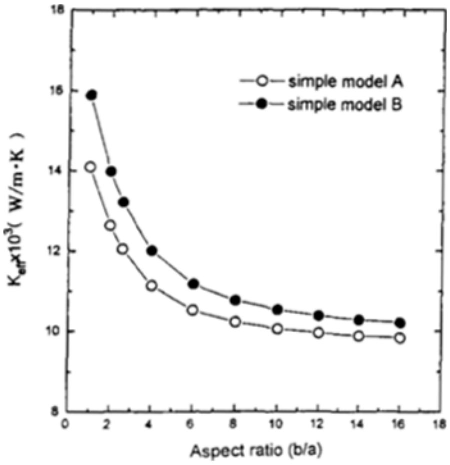


Fig. 13 Effective conductivity of rigid foam/evacuated powder panels with repect to aspect ratio (in case of packaging conductivity K=0.017 W/m·K).

Figure 13 compares the results those have constant thickness vacuum grease (Simple Model A in Fig. 9) or variant thickness vacuum greese (Simple Model B in Fig. 10) in the envelope layers. The influence is not first order. Notice that at an aspect ratio of 10 or more, corresponding to a 30 cm wide panel, the influence of aspect ratio has died out. At this point the heat transfer around the circumference has been minimized.

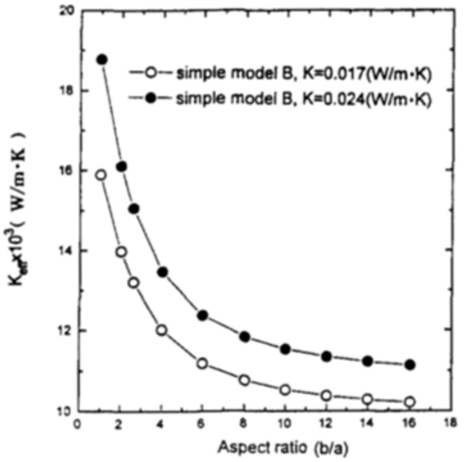


Fig. 14 Effective conductivity of rigid foam/evacuated powder panels with respect to aspect ratio.

Figure 14 shows the influence of the foam conductivity on the overall system behavior. As expected, a lower conductivity foam leads to markedly improved effective conductivity.

6. Conclusions

A prototype glass encapsulated powder filled vacuum panel has been produced. Since the glass encapsulated has very low permeability an inexpensive powder of moderate sized perlite can be used in the panel. The perlite powder exhibits a conductivity between 0.0062 and 0.0068 W/m·K at air pressures below 10 Pa.

When the glass encapsulated pertile panel was embedded in foam a relatively high conductivity of .0205 W/m·K was obtained for the assembly. This value can be significantly reduced to .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.

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