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Fibrous Insulations with Transparent Cover for Passive Use of Solar Energy[1]

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Fibrous thermal insulation protected by a transparent pane instead of an opaque cover applied to the exterior of house walls exhibits an improved efficiency. The fibrous layer and the house wall behind it are heated upon absorption of solar radiation and thermal leakage from the interior of the house is significantly reduced. The transparently covered fibrous insulation is well suited to retrofit old residential and commercial buildings. The optimal design parameters for the fibrous layer are as follows: thickness, 5 cm; density, $10\,\mathrm{kg \cdot m^{-3}}$; fiber diameter, $20\,\mu\mathrm{m}$; and albedo in the visible, $\omega_{\mathrm{vis}} \gtrsim 0.9$.

KEY WORDS: fibrous materials; heat transfer; insulation (thermal); solar energy.

1. INTRODUCTION

In countries with a cold winter climate heating of residential and commercial buildings still contributes markedly to primary energy consumption. A conventional conservation measure is the improvement of thermal insulation, for example, by wrapping house walls with layers of fiber material coupled with installing advanced double- or triple-pane windows.

Recently, transparent or translucent thermal superinsulations have been discussed as promising systems for efficient passive use of solar energy [1] and thus for conservation of primary energy. The translucent wall concept which employs an evacuated aerogel insulation in front of a blackened house wall (Fig. 1) has been considered especially valuable to reduce the heating requirements in buildings. The thermal loss coefficient k for a highly transparent insulation panel with a 15-mm evacuated aerogel spacer

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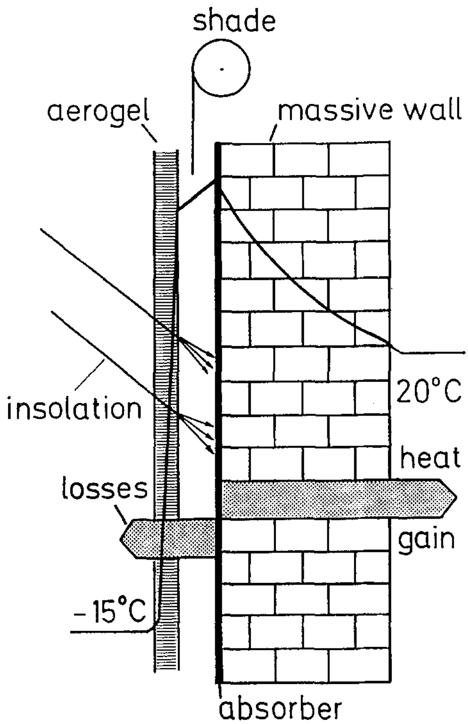

Fig. 1. Transparent house wall insulation using a superinsulating aerogel-filled glass pane system.

can be as low as $0.5\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$. The solar transmission is between 50 and 60%. The heat transfer in aerogels has been studied in detail for monolithic as well as for granular specimens [2]. In particular, the complex coupling between the solid conduction and the radiative transfer in optically thin insulations such as aerogels has been discussed extensively [3].

This paper describes a technically simpler insulation system [4] which also allows passive use of solar energy. Such a system consists of a low-density fibrous insulation on top of a conventional massive house wall with a single glass pane as transparent cover (Fig. 2). Solar radiation is absorbed either within the fibrous insulating layer or at the blackened surface of the wall. The design parameters of this promising simple system with respect to optimal optical and infrared (IR)-optical performance under steady-state conditions are developed. This optimization is a prerequisite for a treatment of the dynamic response, which is the subject of a future study.

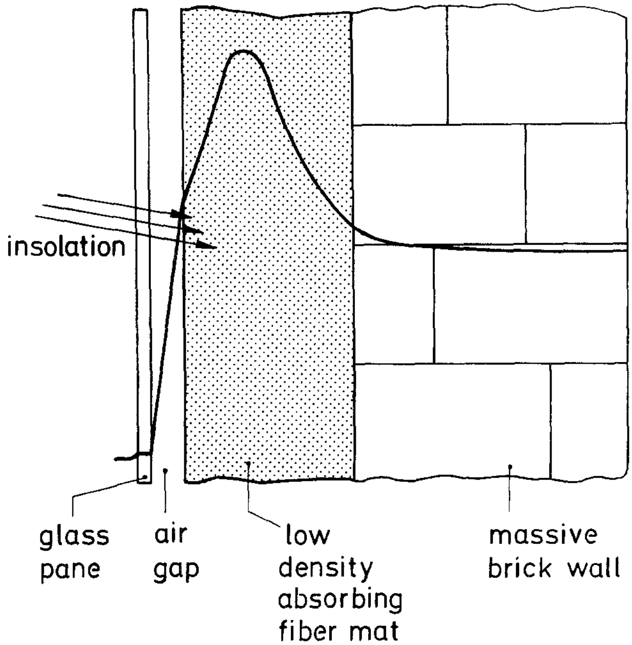

Fig. 2. Thermal insulation system for passive use of solar energy consisting of a low-density fibrous layer and a single glass pane as transparent cover.

2. THERMAL LOSSES VERSUS SOLAR GAINS

Without solar input the thermal loss coefficient k_0 of the layered wall structure in Fig. 2 is determined by the sum of the thermal resistances R_I,

$$\frac{1}{k_0} = R_0 = \frac{1}{\alpha_\mathrm{A}} + \frac{1}{\Lambda_\mathrm{G}} + \frac{1}{\Lambda_\mathrm{F}} + \frac{1}{\Lambda_\mathrm{W}} + \frac{1}{\alpha_\mathrm{I}} \tag{1}$$

$\alpha_\mathrm{A} \approx 25\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ and $\alpha_\mathrm{I} \approx 8\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ are the heat transition coefficients through the outer and inner boundary layers, respectively. Λ_G, Λ_F, and Λ_W are the thermal transfer coefficients in the air gap, the fiber insulation, and the wall, respectively. For a gap of about 10 mm, convection can be neglected and

$$\Lambda_\mathrm{G} = \Lambda_\mathrm{R} + \Lambda_\mathrm{AIR} = \varepsilon_\mathrm{I} 4\sigma T_\mathrm{R}^3 + \lambda_\mathrm{AIR}/d_\mathrm{G}$$

with ε_I being the emittance of the inside of the protective pane. The emittance of the fiber layer is assumed to be 1. If the protective cover has a low emittance ($\varepsilon_\mathrm{I} \approx 0.1$) on its inside, $\Lambda_\mathrm{R} \approx 0.5\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ can be estimated (otherwise $\Lambda_R \approx 4.5\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$). With the thermal conductivity of air $\lambda_{AIR} = 0.025\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ and the gap width $d_G \approx 0.012$ m, we get $\Lambda_G \approx 2.6\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ for the low-emittance pane and $6.6\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ otherwise.

For the fiber layer, a thermal conductivity $\lambda_F \approx 0.03\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ and a thickness $d_F \approx 0.04$ m are assumed, while for the massive wall $\lambda_W \approx 1\ \mathrm{W \cdot m^{-1} \cdot K^{-1}}$ and $d_W = 0.25$ m are used.

This leads to a thermal loss coefficient, k_0, as

$$\frac{1}{k_0} \approx \left\{\frac{1}{25} + \frac{1}{2.6} + \frac{0.04}{0.03} + \frac{0.25}{1} + \frac{1}{8}\right\} \mathrm{m^2 \cdot K \cdot W^{-1}}$$

or $k_0 \approx 0.47\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$.

Taking into account that the fiber layer and the black wall absorb part of the solar flux and that the thermal losses thus are partially compensated, the system may be described with an effective loss coefficient,

$$k_{EFF} = k_0 - q_{SOL}\, t\eta / \Delta T \tag{2}$$

where $q_{SOL}\, t$ is the solar flux, which is transmitted through the glass pane of transmittance t and impinges onto the fiber layer. ΔT is the mean difference between the temperature inside and that outside the house, T_I and T_E, respectively. η is an efficiency, equivalent to the fraction of the solar flux which is absorbed and transferred into the house. The quantity $q_{SOL}/\Delta T$ in Eq. (2) is given by the climatic conditions, while k_0, t, and η can be chosen according to the technical design.

With the introduction of the solar gain coefficient

$$k_{SOL} = q_{SOL} / \Delta T \tag{3}$$

Eq. (2) can be rewritten as

$$k_{EFF} = k_0 - k_{SOL}\, \eta t \tag{4}$$

A plot of k_{EFF} versus k_{SOL} (see Fig. 3) gives a straight line with a negative slope, equal to ηt. The thermal losses from the interior to the environment vanish for

$$k_{SOL,0} = k_0 / \eta t \tag{5}$$

Equation (4) then becomes

$$k_{EFF} = k_0 (1 - k_{SOL} / k_{SOL,0}) \tag{6}$$

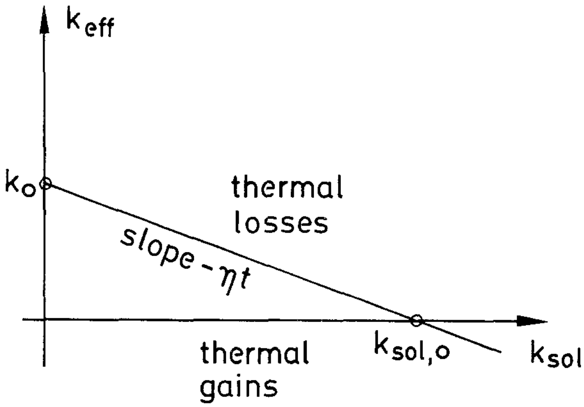

Fig. 3. Effective thermal loss coefficient k_{EFF} versus gain coefficient $k_{SOL}=q_{SOL}/\Delta T$. k_0 is the thermal loss coefficient without solar input. k_{EFF} vanishes for a solar gain coefficient $k_{SOL}=k_{SOL,0}$. The slope of the straight line is determined by the efficiency η (which is the fraction of the solar flux absorbed by the fiber layer or the wall and which is transfered into the house) times the transmission t of the protective glass pane.

Negative losses, i.e., thermal gains, occur if

$$k_0 < k_{SOL}\,\eta t$$

Under stationary conditions it is not intended that heat up of the massive wall or the interior of the house occurs (although in the dynamic reality it would have to, in order to make up for hours without solar input). Therefore optimization of the insulation system for a minimum solar input is undertaken according to Eq. (5). The parameters k_0, t, and η can be changed by constructive means. k_0 is most strongly influenced by the thickness d_F, density ρ, and fiber diameter D of the fibrous layer, the air gap d_G, and the emittance ε_I of the glass pane.

The transmittance t of the pane for solar radiation is of the order of 82% for a noncoated pane; for a low-emittance pane $t \approx 60\%$ can be assumed.

Two extreme cases are discussed.

(i) The total transmitted solar flux $q_{SOL}\,t$ is absorbed at the outer surface of the fiber layer. If no net heat flux is to be transferred into or out of the house, the temperature of the absorbing layer has to be equal to T_I, the temperature of the interior. Thermal losses then are determined by the resistance of the air gap (α_A is assumed to be infinitely large):

$$\Delta T\,\Lambda_G = q_{SOL,0}\,t \tag{7}$$

With $\varepsilon_I = 0.1$ and $t = 0.6$, Eqs. (3) and (5) give

$$k_{SOL,0} = \Lambda_G/t = 4.3\ \mathrm{W \cdot m^{-2} \cdot K^{-1}} \tag{8}$$

and

$$\eta t = k_0/k_{SOL,0} = 0.47/4.3 \approx 11\% \tag{9}$$

if the estimate along Eq. (1) is inserted. The efficiency is $\eta \approx 18\%$.

Thus a solar flux per temperature difference $q_{SOL}/\Delta T = k_{SOL,0} = 4.3\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ is necessary to decouple the interior of the house from the environment thermally. A decrease in gap width would increase Λ_G and thus require a larger solar input for $k_{EFF} = 0$. Installation of a noncoated window also would require a larger $k_{SOL,0} = 8\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$, as in this case Λ_G becomes $\approx 6.6\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$.

(ii) The total solar flux is assumed to pass through the air gap and the insulating nonabsorbing, but weakly scattering layer. The absorption of the solar flux occurs at the surface of the massive wall, which in this case is required to have the temperature T_I for vanishing thermal losses. As the resistances of the air gap and fiber layer are now in series, it follows that

$$\Delta T \left\{ \frac{1}{\Lambda_G} + \frac{1}{\Lambda_F} \right\}^{-1} = q_{SOL,0}\, t t_F \tag{10}$$

with

$$\Lambda_F = \frac{(16/3)\,\sigma T_R^3}{1 + (3/4)\,\tau_{IR}} + \frac{\lambda_{AIR}}{d_F} \tag{11}$$

τ_{IR} is the optical thickness in the IR, and t_F the transmission of solar radiation through the fiber layer. The latter can be calculated according to

$$t_F = (1 + 3\tau_{VIS}/4)^{-1} \tag{12}$$

where τ_{VIS} is the optical thickness of the fiber layer in the visible [5].

According to Eq. (3)

$$k_{SOL,0} = \left\{ \frac{1}{\Lambda_G} + \frac{1}{\Lambda_F} \right\}^{-1} t^{-1}(1 + 3\tau_{VIS}/4) \tag{13}$$

Correspondingly the efficiency is [see Eq. (5)]

$$\eta = k_0 \left\{ \frac{1}{\Lambda_G} + \frac{1}{\Lambda_F} \right\} (1 + 3\tau_{VIS}/4)^{-1} \tag{14}$$

If τ_{IR} and τ_{VIS} are properly designed, the solar flux needed to compensate the thermal losses can be considerably smaller than in case i. The air gap and the low-emittance coating are not necessary on case ii. With typical values $\tau_{VIS} \approx 1$, $\tau_{IR} \approx 6$, $d_F = 0.05$ m, $d_G = 0$, and $t = 0.8$, we get $k_{SOL,0} \approx 3.9\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ and $\eta \approx 0.57$.

In the more general case with absorption in the fiber system, the solar flux decreases multiexponentially. Thus, via conduction and reemission of thermal radiation, the temperature distribution is strongly modified. Calculations can be performed numerically by solving the coupled radiation–conduction transfer equation, as discussed in the following section.

3. DESIGN PARAMETERS FOR THE FIBER LAYER

The propagation of solar and thermal flux and optimization of the fibrous layer are treated quantitatively. For this purpose the following parameters have to be varied:

the albedo ω_{VIS} in the visible,

the density ρ_F and thickness d_F of the fiber insulation, and

the fiber diameter D.

ω_{VIS} strongly influences the reflectance R_{VIS} of the insulation and the coupling between solar and thermal heat flux. Density ρ_F and thickness d_F determine the optical thickness τ_{VIS} and τ_{IR} in the visible and the infrared spectral region, respectively:

$$\begin{aligned} \tau_{VIS} &= \rho_F\, d_F\, e_{VIS} \\ \tau_{IR} &= \rho_F\, d_F\, e_{IR} \end{aligned} \tag{15}$$

where e is the specific extinction coefficient. High-density absorbing insulations could be expected to give similar results as estimated in case i, while for low-density purely scattering systems, case ii applies. The fiber diameter D influences the spectrally averaged specific extinction coefficients e_{VIS} and e_{IR} in the visible and infrared. These quantities are related to the fiber extinction cross section Q_{EXT} by

$$e = 4Q_{EXT}/(\pi\rho_0 D) \tag{16}$$

where ρ_0 is the solid density of the fiber material. The wavelength-dependent cross sections are calculated from the IR complex index of refraction of glass [6] via Mie scattering theory [7], assuming randomly oriented fibers. The anisotropy of scattering is included by scaling the extinction cross sections with the anisotropy factor derived from the scattering phase function [8]. The spectral values have been averaged with the Rosseland distribution function for $T = 290$ K for the infrared and $T = 6000$ K for the solar extinction (assuming $n = 1.5$).

In order to allow a deep penetration of the solar flux into the fiber layer, but to provide strong attenuation of the heat flux, the ratio

$$e_{\mathrm{VIS}}/e_{\mathrm{IR}} = \gamma \tag{17}$$

ought to be small compared to one. This is approximately valid for fibers with $D > 10$ μm (see Fig. 4).

In the case of purely scattering fibers ($\omega_{\mathrm{VIS}} = 1$), infrared flux and solar flux are decoupled and the calculations can be simplified. The transmitted solar flux $q_S t t_F$ is absorbed at the surface of the wall. The gain coefficient $k_{\mathrm{SOL},0}$ then is described by Eq. (13). From this equation, with τ_{IR} as the variable, the optimal optical thickness $\tau_{\mathrm{IR,OPT}}$ is obtained for minimal $k_{\mathrm{SOL},0}$, assuming $d_G = 0$:

$$\tau_{\mathrm{IR,OPT}} = \frac{4}{3}\left\{\left[\frac{(1-\gamma)}{\gamma}\frac{4\sigma T_{\mathrm{R}}^3}{\lambda_{\mathrm{AIR}}/d_{\mathrm{F}}}\right]^{1/2} - 1\right\} \tag{18}$$

$$k_{\mathrm{SOL},0} = \frac{\lambda_{\mathrm{AIR}}}{d_{\mathrm{F}} \cdot t}\left\{(1-\gamma)^{1/2} + \left(\gamma\frac{4\sigma T_{\mathrm{R}}^3}{\lambda_{\mathrm{AIR}}/d_{\mathrm{F}}}\right)^{1/2}\right\}^2 \tag{19}$$

With $\gamma = 0.24$ for glass fibers with $D > 15$ μm (Fig. 4), $d_F = 50$ mm, $t = 0.82$, and $T_R = 280$ K, a value $k_{\mathrm{SOL},0} = 3.6\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$ is obtained for $\tau_{\mathrm{IR}} = 6.2$. According to Eqs. (15) and (16) and using $Q_{\mathrm{EXT,IR}} = 0.82$ (Fig. 4), this corresponds to a fiber diameter of $D = 37$ μm and a density $\rho_F = 10\ \mathrm{kg \cdot m^{-3}}$. The variation of $k_{\mathrm{SOL},0}$ with γ is shown in Fig. 5.

In the more general case with $\omega_{\mathrm{VIS}} < 1$ the net heat flux is determined by solving the appropriate equations for the IR and visible radiative transfer in the insulation (see, e.g., Ref. 9). Heat transfer by gas conduction and IR and visible radiative transfer are coupled by the requirement that the divergence of the net energy flux

$$q = -\lambda(dT/dx) + q_{\mathrm{IR}} + q_{\mathrm{VIS}} \tag{20}$$

vanishes for stationary conditions. q_{IR} and q_{VIS} are the infrared and visible radiative fluxes.

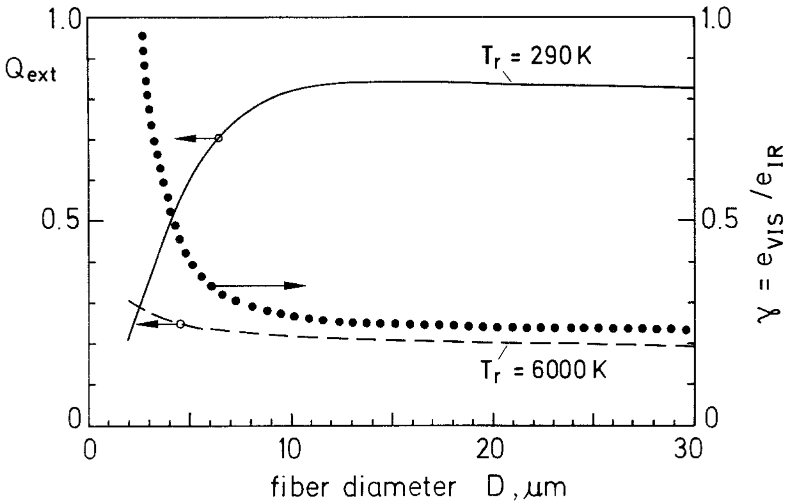

Fig. 4. Spectrally averaged relative cross section Q_{EXT} for glass fibers in the visible ($T_{\mathrm{R}} = 6000$ K) and in the IR ($T_{\mathrm{R}} = 290$ K) as well as the ratio $\gamma = e_{\mathrm{VIS}}/e_{\mathrm{IR}}$ versus fiber diameter D.

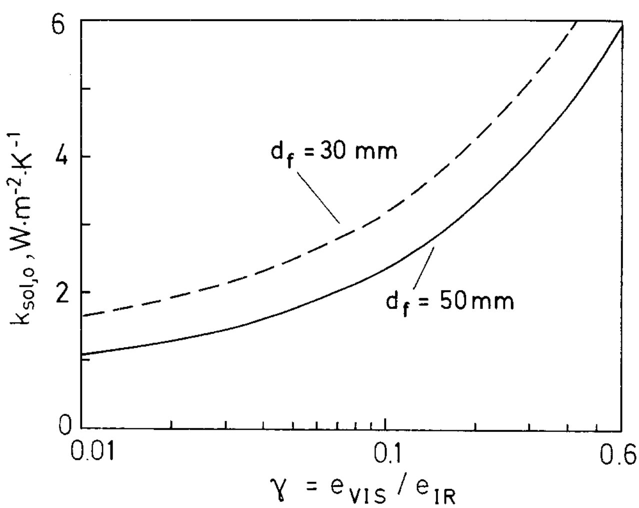

Fig. 5. Gain coefficient $k_{\mathrm{SOL,0}}$ (for vanishing k_{EFF}) versus $\gamma = e_{\mathrm{VIS}}/e_{\mathrm{IR}}$ for fiber layers with thicknesses $d_{\mathrm{F}} = 30$ and 50 mm.

For the solution of the resulting system of integro differential equations the three-flux method proposed by Kaganer [10] was used. The high accuracy of this method has been demonstrated [11], when experimentally derived apparent conductivities of low-density fibrous insulations were compared to the predictions of the three-flux solution for a gray disperse medium.

The boundary conditions are determined by the properties of

- the glass pane (transmittance t_1 and reflectance r_1 for solar radiation, emittance ε_I in the IR, temperature T_1),
- the air gap (gap width d_G, air conductivity λ_{AIR}),
- the fibrous insulation (thickness d_F, conductivity λ_F, albedo ω_{IR} and ω_{VIS}, optical thickness τ_{IR} and τ_{VIS}), and
- the wall construction (surface emittance ε_2, reflectance in the visible r_2, coefficients A_W and α_i).

The absorption coefficient A_{VIS} of the fibers can be increased by staining them (e.g., by a small amount of soot). As the scattering coefficient S_{VIS} in the visible (obtained by Mie theory) is not expected to change considerably when A_{VIS} is increased, the extinction coefficient $E_{VIS} = A_{VIS} + S_{VIS}$ and, hence, the optical thickness τ_{VIS} are increased. Accordingly the albedo

$$\omega_{VIS} = S_{VIS}/E_{VIS} \tag{21}$$

is decreased. Staining the fibers in the visible has little effect in the IR, as the absorption coefficient of soot in the IR is far lower than in the visible and S_{IR} is larger than S_{VIS} if the fiber layer is properly designed.

4. RESULTS AND COMPARISON WITH OTHER SYSTEMS

In Fig. 6 the calculated dependence of $k_{SOL,0}$ on the reflectance $R_{\infty,VIS}$ and albedo ω_{VIS} is shown. $R_{\infty,VIS}$ characterizes the reflectance of a fiber layer which is optically thick in the visible. The total thickness $d = d_G + d_F = 50$ mm of the transparent insulation systems was kept constant and either a 12-mm air gap or no gap was considered. The lowest values for both high- and low-emittance glass covers are found for large fiber diameters ($D = 30\ \mu$m) and low densities ($\rho = 10\ \mathrm{kg \cdot m^{-3}}$). Here $k_{SOL,0}$ is rather insensitive to the reflectance in the visible. For a transparent insulation system, including a low-emittance glass pane, $k_{SOL,0}$ is as low as $2.9\ \mathrm{W \cdot m^{-2} \cdot K^{-1}}$. The optimal albedo ω_{VIS} is in the range of 0.9 (corresponding to a reflectance $R_{\infty,VIS} \approx 0.4$). If the total thickness is

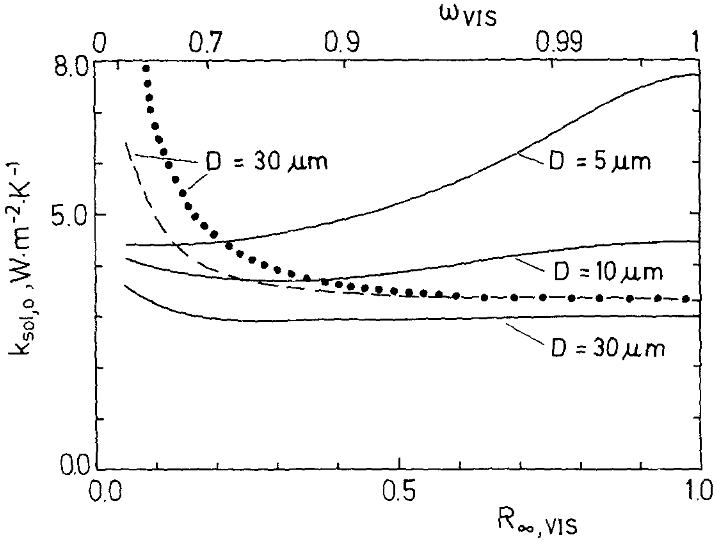

Fig. 6. Gain coefficient $k_{SOL,0}$ versus reflectance of fiber layer in the visible spectral range, $R_{\infty,VIS}$, and albedo ω_{VIS}. Solid lines are for a coated glass pane ($\varepsilon = 0.1$) with a 12-mm air gap, the dashed line depicts the results for an uncoated glass pane ($\varepsilon = 0.9$), and the dotted curve gives gain coefficients for a system with a coated glass pane but without an air gap. *D* is the fiber diameter.

reduced to $d = 35$ mm, a slight increase in $k_{SOL,0}$, to 3.1 $W \cdot m^{-2} \cdot K^{-1}$, is observed.

For the low-emittance glass pane system an air gap is absolutely necessary. Without the air gap $k_{SOL,0} \geqslant 4.1$ $W \cdot m^{-2} \cdot K^{-1}$ results, which is not shown in Fig. 6. Systems with high-emittance glass panes ($\varepsilon_1 = 0.9$) either with or without an air gap provide a minimal $k_{SOL,0} \approx 3.3$ $W \cdot m^{-2} \cdot K^{-1}$ for $R_{\infty, VIS} = \omega_{VIS} = 1$ (Fig. 6).

For comparison it is pointed out that for nonevacuated aerogel insulations (see Fig. 1) of about 15- to 20-mm thickness, values for $k_{SOL,0} \approx 2.5$ $W \cdot m^{-2} \cdot K^{-1}$ are feasible. An evacuated aerogel insulation provides an extremely low solar gain coefficient $k_{SOL,0} \approx 1$ $W \cdot m^{-2} \cdot K^{-1}$. It would have to be equipped, however, with a durable vacuum-tight metal rim seal. Organic capillary structures with 10-cm thickness and protective glazing on both sides can provide $k_{SOL,0} \approx 1.5$ $W \cdot m^{-2} \cdot K^{-1}$.

5. CONCLUSIONS

Transparently covered fiber insulations are technically simple. Recommended parameters are a layer of about 5-cm thickness of weakly absorbing fibers 20–30 μm in diameter at a density of $10\,\mathrm{kg \cdot m^{-3}}$ and a noncoated glass pane as a cover. For a steady-state insulation of about $3\,\mathrm{W \cdot m^{-2}}$ for each degree K temperature difference between the interior of the house and the environment, thermal losses can be compensated with such a passive solar system. Overheating of the wall is less critical than with the design in Fig. 1. Climatic data show that the above insulation is available quite often even in middle Europe. In the near-future an investigation of the nonstationary problem including storage effects and limited sunshine periods is planned.

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