*Heat-Transport and Solar Transmission Through Windows with Low-Emitting Coatings**

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ABSTRACT

The thermal performance of a double glazed window with a low emitting coating is studied. Three types of coatings are considered: single noble metal-films; noble metal-based triple-layers ZnS/M/ZnS; and sprayed SnO_2-films.

The quantities calculated are the total heat-flow, the U_l-value, and the pane-temperatures. Calculations are made both for night-time and for daytime with varying solar radiation-intensity. Different semi-empirical expressions for the convective transfer give essentially the same results.

Particular attention is given to the net effect of absorption in the coating. It is found that with the coating on the inner pane, about 70 percent of the absorbed solar energy is effectively transferred as heat into the room.

In an overall comparison with strong insolation considered, the SnO_2-films show the best properties even if the triple-layers have higher solar transmission.

INTRODUCTION

The *increasing price of energy has made energy-conservation in* domestic houses an important issue. The first response to this end has naturally been to improve the insulation of the buildings. The U_L-value of a modern wall is therefore coming down to, or even below,

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0.25 W/K,m². In that situation it becomes logical to turn the attention towards the windows and their influence on the heat-balance of a building. Approximately 20 percent of the heat-losses in a normal house passes through the windows [1]. From a Scandinavian perspective, a "normal" window is double-glazed and heat losses in darkness corresponding to a U_l-value around 3.0 W/K,m². A natural first reaction might therefore be to reduce the total window area when heat-conservation becomes important. It is, however, important to realize that windows are also a significant *source* of energy in the form of direct or indirect sunlight. Although the high U_l-value makes them a major heat-leak, many windows do in fact give a net positive contribution to the heat balance of the house. The appropriate action should therefore be to reduce the heat-flow out of the window in a way that does not prevent the solar radiation from entering the room.

One way to achieve this, is to increase the number of window panes. As a rule of thumb one can say that the heat-flow in darkness is inversely proportional to the number of panes. The loss of daylight is less than 15 percent for each new pane. In cold countries, new houses are, therefore, commonly constructed with three-pane windows and even four panes are common. For several reasons, at least two of these panes are permanently sealed to one another with a polymer seal. The durability of this seal has become a problem and the increasing weight of the windows makes the construction more expensive.

In view of these difficulties, an alternative approach has received increasing attention lately, that is, to use radiation control to reduce the heat-flow through the window. This is possible with a low-emitting film on one of, or between, the window panes [2]. In this work, we shall discuss the performance of different coatings of this nature and demonstrate the effect on the net heat balance.

The heat losses through a window take place via radiation and convection. Conduction in air is negligible compared to convection. The thermal resistance of the glass panes is relatively small compared to the thermal resistance of the window glass-air system. If we take a double-glazed window as a starting point, the proportions between radiation and convection change as we move through the construction. The detailed results for night-time are shown in Figure 2a, but we can quite generally say that the radiation effects are important, particularly between the panes. Strictly speaking, this fact makes the concept of U_L-value nonvalid, but for small temperature differences, the expression can be linearized and even the radiative transport expressed as a product of a U_L-value and a temperature difference.

The spectral variation of the radiation is primarily determined by the black-body spectrum for room-temperature. This means that the spectral content of the heat-radiation is displaced towards long wavelengths, typically, 10–40 μm. In this region, the glass is nearly opaque, with 10 percent reflectance. If we assume that convection is negligible and heat is only transported by radiation, we can approximately state that 90 percent of the heat-radiation from the room will be absorbed and 10 percent reflected by the glass in a single-pane window. This absorbed heat will then be reradiated by the glass, half towards the outside and half back into the room. Thus, the net result is that only 45 percent of the radiation emitted from the room will be lost through the window, which means that the opacity of the glass in the IR gives an important contribution to the heat insulation. The radiation losses can be further suppressed, however, by a heat-reflecting layer on one or several surfaces of the window. This film should necessarily be transparent for visible light and preferably transparent for the entire solar spectrum. A coating with this property could be a very thin metal film, a multilayer based on a metal film or a heavily doped wide-bandgap semiconductor such as SnO_2 or In_2O_3 [3]. In the present work, the thermal and optical function of a domestic window with these different coatings will be investigated by means of heat-transfer calculations.

A number of such calculations have been performed earlier [4,5,6], usually treating the influence of the low-emitting coating in a simplified manner. In the treatment of different types of selective coatings, the internal absorptance of the coating is often assumed to be negligible. The aim with this work is to compare the performance of the major different types of selectively transmitting layers coated on window glass, including the effects of absorption. The net energy-flow, i.e., the sum of heat and solar radiation through the window, is analyzed in detail. Since calculations require several choices of heat-transfer coefficients in the thermal network, these coefficients are discussed in the next section. A few of our present conclusions have appeared in previous publications [7].

THERMAL MODEL

Figure 1 shows a schematic illustration of a double-glazed window together with a network, which simulates the thermal flow through the window. The total flow can be analyzed in three different regions: flow between (a) the room and the inner glass; (b) the two glasses; and (c) the outer glass and the exterior. In each region, the heat flow consists of a radiation and a convection part. The contribution from conduction is assumed to be included in the convection part. The problem is linearized

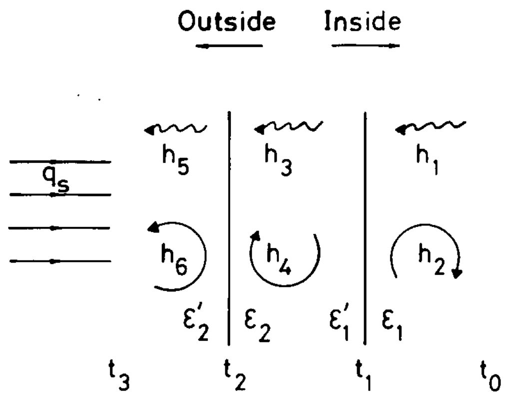

Figure 1a. A schematic illustration of the heat transfer model. q_s is the insolation, h_i the heat transfer coefficient, ε_i the emittance and t_i the temperature.

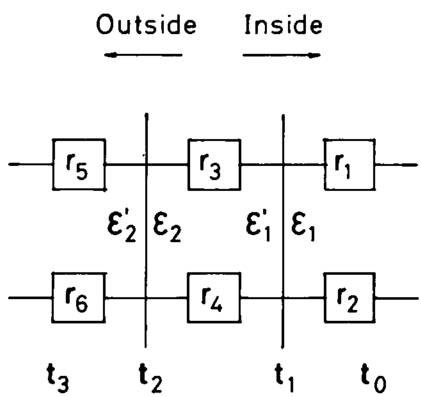

Figure 1b. The equivalent thermal network for the heat transfer through the window, $r_i = 1/h_i$.

so that each part of the heat-flow is given as the product, a heat-transfer coefficient, and a temperature-difference.

The heat-transfer coefficients are given by the following expressions:

h_1—radiation from the room to the inner glass surface.

h_2—convection from the room to the inner glass surface. The sum of these two terms can be obtained from reference [8].

$$h_1 + h_2 = 8 \text{ W/m}^2\text{K}$$

The description of heat-transfer between the room and the inner pane, $h_1 + h_2$, creates a specific problem since solar-absorption in a coated inner-glass may raise the glass-temperature above room-temperature and simultaneously change the direction of heat-transfer. We have, however, used the identical heat-transfer coefficient independent of the direction of heat-transfer. To investigate the reliability of the used coefficient, the following approaches with detailed separate expressions for h_1 and h_2 have been tested [4,9]:

$$h_1' = \frac{\sigma\varepsilon_1(\varepsilon_0 t_0^4 - t_1^4)}{(t_0 - t_1)}$$

$$h_2' = 3.5 + 0.09\,|t_0 - t_1|$$

where h_1' is derived under similar assumptions as h_5 below, and σ is the Stefan Bolzmann constant.

As a third alternative for the convective transfer, we have also tested [10]:

$$h_2'' = 1.98\,|t_0 - t_1|^{0.25}$$

Network calculations based on these different expressions for h_1 and h_2 gave almost identical results.

In the next region, we have used the two transfer coefficients:

h_3—radiation between the two glasses is approximated as that between two infinite parallel plates with the effect of multiple reflections included [11],

$$h_3 = \frac{\sigma(t_1^2 + t_2^2)(t_1 + t_2)}{\left(\frac{1}{\varepsilon_1'} + \frac{1}{\varepsilon_2} - 1\right)},$$

and

h_4—convection between the two glasses equations of de Graaf and van der Held [12] for an air-gap of 20 mm between the glasses was used,

$$h_4 = 0.73(t_1 - t_2)^{0.37}.$$

For the heat transfer to the surroundings:

h_5—radiation between the outer glass and the exterior [9] was used,

$$h_5 = \frac{\sigma\varepsilon_2'(t_2^4 - \varepsilon_3 t_3^4)}{(t_2 - t_3)}.$$

This transfer coefficient was derived assuming a view-factor of unity and that none of the radiation leaving the window surfaces is reflected back from the surroundings. In order to evaluate the radiation exchange between a surface and the sky, different authors suggest that the effective sky temperature should be lower than the actual air temperature, or that the sky emittance should be lowered [13,14]. But this problem is fortunately unimportant in this context, because the heat-losses from the outer glass are dominated by the convective part $h_6 \Delta t$. For simplicity, we have treated the sky as a blackbody ($\varepsilon_3 = 1$) of air temperature. The emittance of the bare glass is calculated from reflectance measurements at normal incidence [7] (Table 1). This value, $\varepsilon = 0.91$, is the average of values used elsewhere. Literature values vary, e.g., $\varepsilon = 0.94$ [15] and $\varepsilon = 0.88$ [13] can be found. The calculation of convective heat-losses between the outer pane and the surroundings are more sensitive to the choice of wind velocity than to the choice of a specific expression. We have used for h_6—convection between the outer glass and the exterior [13]:

$$h_6 = 5.7 + 3.8\ v$$

where v is the wind velocity in m/s with the numerical value v = 5 m/s.

Table 1. Optical Parameters of the Coated Window-glass Used in the Calculations.

Coating [nm]	T_{SOLAR}	R_{SOLAR}	A_{SOLAR}	ε_{293}
Ag				
5	67.6	26.4	**6.0**	**6.5**
10	45.0	50.1	4.9	**2.8**
15	29.7	66.3	4.0	**1.7**
20	**19.8**	76.8	3.4	1.3
ZnS/Ag/ZnS				
45/5/45	80.2	13.2	**6.6**	**6.7**
45/10/45	74.4	18.8	**6.8**	**2.8**
40/15/40	63.0	30.6	**6.4**	**1.8**
40/20/35	50.1	43.9	**6.1**	**1.3**
Au				
5	67.1	21.0	**11.9**	14.6
10	47.8	38.5	**13.7**	7.4
15	34.0	51.6	**14.4**	5.0
20	24.6	60.9	**14.5**	3.7
ZnS/Au/ZnS				
50/5/50	76.2	13.8	**10.0**	15.1
45/10/45	71.5	15.3	**13.2**	7.5
45/15/45	63.3	20.0	**16.7**	5.1
40/20/40	53.0	30.9	**16.1**	3.8
SnO_2(Sb)	60.8	10.9	**28.3**	15.9
none	85.9	7.0	7.1	91.0

The calculations also require the radiation parameters T_{SOLAR} and R_{SOLAR} for the different coated glasses. The details of these measurements are found elsewhere and the results are summarized in Table 1.

An energy balance is written for each glass using the following assumptions: (1) steady-state conditions; (2) no heat loss through frames; (3) optical properties averaged over the solar spectrum; (4) averaged glass temperatures; and (5) glass perpendicular to sun.

An energy balance at the inner glass yields,

$$(h_1 + h_2)(t_0 - t_1) + a_1 q_s = (h_3 + h_4)(t_1 - t_2)$$

and at the outer glass,

$$(h_3 + h_4)(t_1 - t_2) + a_2 q_s = (h_5 + h_6)(t_2 - t_3)$$

where multiple reflections between the glasses give,

$$a_1 = \frac{T_2 A_1}{1 - R_1' R_2} \quad a_2 = A_2 \left(1 + \frac{T_2 R_1'}{1 - R_1' R_2}\right)$$

a_1 and a_2 represent the total absorption of insolation in the two glasses, respectively. Multiple reflections inside each glass are included in the measured values of T and R given in Table 1.

A computer program solves the equations by searching for the glass temperatures which satisfy the heat balance equations. The program calculates the glass temperatures, the heat transfer, the overall heat transfer coefficient U_L, the total solar transmission and reflection, and the solar absorption in glass 1 and glass 2. In all calculations, a room temperature of 20°C (t_0 = 20°C) and an outdoor temperature of 0°C (t_3 = 0°C) were assumed.

HEAT TRANSFER IN DARKNESS

In darkness, only the emittance is needed among the optical parameters to perform the calculations. The heat transfer through a normal double-glazed window is presented in Figure 2a. The radiation and convection contributions are comparable for the heat transfer between the room and the inner glass. Between the panes, the radiation part is larger than the convection part, and the forced convection dominates the heat-losses from the outer glass. When one of the surfaces facing the air-gap is coated with a low-emitting film, the radiation transfer between the glasses is reduced, and the overall heat-transfer coefficient U_L is considerably decreased as seen in Figure 2b. As can be seen in the expressions for h_3, identical results are obtained if the inside of the outer glass or the outside of the inner glass is coated. There is no reason to

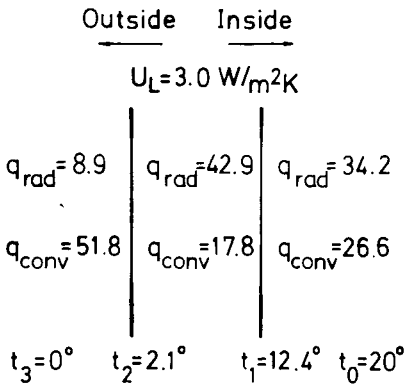

Figure 2a. Heat transfer through a normal window.

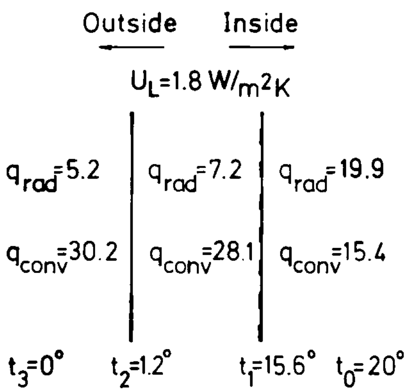

Figure 2b. Heat transfer through a window with a low emitting coating on the outside of the inner glass ($\varepsilon_1' = 0.1$).

coat both these surfaces since one film depresses the radiation enough to make the convection dominating. As can be expected from Figure 2a, the effect on U_l is larger if one of the air-gap surfaces is low-emitting than if the inner surface of the inner glass is. This is clearly demonstrated in Figure 3. Because of the large convection heat transfer to the surroundings, almost nothing is gained by coating the outside of the outer glass by a low-emitting film.

It is interesting to note in Figure 3, that the derivative of U_L grows with decreasing ε. This implies that a search for coatings with very low ε is worthwhile. Numerically, the increasing slope of U_L stems from the fact that $\Delta t = t_1 - t_2$ increases with decreasing ε.

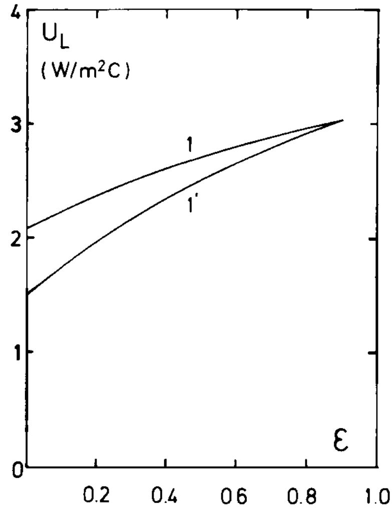

Figure 3. The overall heat transfer coefficient vs. emittance for a coating on the side (1) and outside (1') of the inner glass.

HEAT TRANSFER UNDER INSOLATION

When the thermal and optical function of the window under insolation is investigated, it is necessary to know both of the optical parameters: reflectance, transmittance, and absorptance over the solar spectrum and the thermal emittance of the coating. The detailed properties of the investigated coatings are presented in Table 1. These coatings are believed to be representative for the different types of materials and configurations that can be used as solar-adapted coatings on windowpanes of glass or plastic. The coatings can be classified into three categories: (1) single metal films; (2) metal films sandwiched between dielectric layers; (3) a wide bandgap semiconductor doped to a suitable density of conduction electrons.

In the first category, mainly noble metal films have been considered. Their high conductivity ensures high IR reflectance and if prepared thin enough, they allow high visible transmission. The triple layers are designed as an interference filter where the dielectric is given the thickness which induces high transmission in the visible. Noble metals are common also in this case and we have chosen silver and gold for comparison in both categories 1 and 2. The dielectric should have very small absorption and a sufficiently high refractive index. We have selected zinc sulfide, which is commonly used as an antireflection coating. It has a high refractive index and acceptable mechanical strength. In the third category, there is a limited number of semiconductors with a bandgap large enough (i.e., >3 eV) to transmit visible radiation that can be doped so as to obtain high IR reflectance with a plasma edge in the wavelength interval 2–3 μm. We have chosen tin oxide doped with antimony as a typical material in this group, but similar or slightly better results have been reported for doped indium oxide and cadmium stannate [3].

For the calculation solar transmission, solar reflection and thermal emittance are needed for each coating. In the first two cases, we have chosen to calculate these parameters from optical constants available in the literature. The bulk optical constants for the noble metals are well established and their validity was investigated for thermally evaporated films. The theoretically predicted data in Figure 4 agreed with measured data down to a film-thickness of 20 nm for Au and 12 nm for Ag [16]. Other investigations have shown that even Au films can be prepared with optical constants resembling those of bulk metals down to a film thickness of 10–12 nm [17]. The ZnS films in the triple layers were

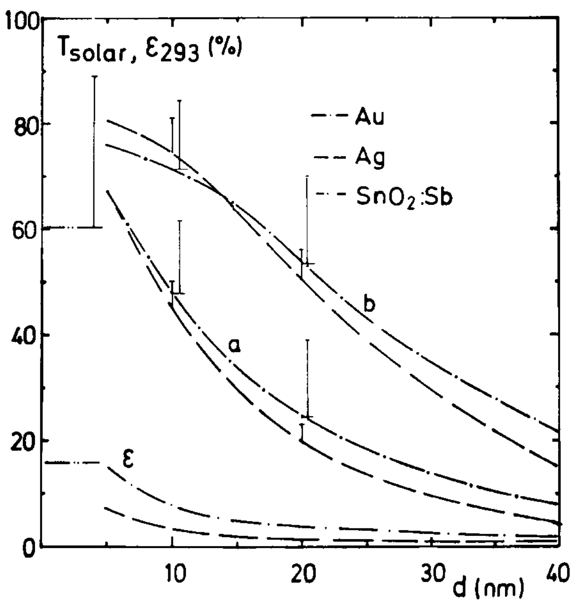

Figure 4. Integrated solar transmittance and emittance vs. metal thickness for metal films and optimized triple layers on window glass. These data are calculated from bulk values for the optical constants. The properties of the experimental SnO_2 coating is also noted. The height of the bars indicate the magnitude of the absorption in the coating. a: Single metal, Au: 15 nm, Ag: 15 nm. b: ZnS/M/ZnS, Au: 45/15/45 nm, Ag: 40/15/40 nm.

assumed non-absorbing and their thicknesses systematically chosen to optimize the solar transmission [18].

For the SnO_2 films, in contrast, we have used experimental T_{solar}, R_{solar}, and ε_{293} values for our pyrolytic films on glass [19]. To increase the IR reflectance of the film it was doped with Sb from an $SbCl_3$ added to the spray solution. The optical properties of these films had not been optimized but they are comparable to SnO_2 films prepared by others [20].

In summary, we can say that the calculated values for the two first categories of coatings in Table 1 and Figure 4 should be valid for the thicknesses treated but with a possible overestimation of the transmission. The experimental values for the tin oxide layer do not represent an optimum and can surely be improved.

Figure 5 presents the total energy transfer to the room, i.e., the sum of directly transmitted solar radiation and heat which enters the room, as a function of insolation. At low values of insolation, the reduction of heat losses is greater than the reduction of the transmitted solar radiation through a coated window, so that any of the coatings improves the properties of the window.

When the insolation becomes higher than 70 W/m², however, the enhanced thermal insulation cannot balance the low transmittance of the bare metals and the uncoated window shows better performance than the metal-coated. The increased transmittance of the triple-layers

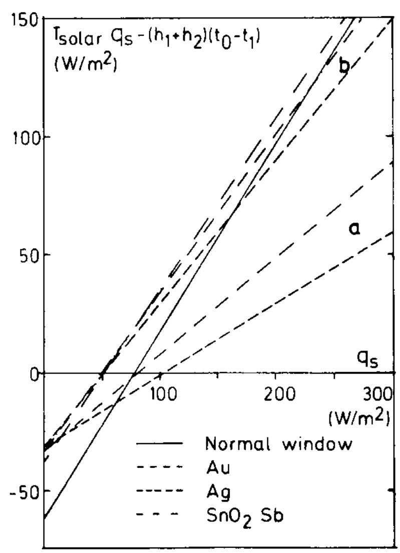

Figure 5. The net energy flow from a window into a room as a function of insolation q_s, with coatings as indicated. Metal- and ZnS-thicknesses as in Figure 4.

and the oxide films mean that they give a higher net energy transfer to the room than a normal window up to a solar radiation of 160 W/m², 230 W/m², and 320 W/m² for the silver layers, gold layers, and the oxide coatings, respectively. A comparison between the curves at, e.g., 100 W/m² of insolation, shows that, with respect to the uncoated window, the bare Au coating causes a loss of 11 W/m², while the doped SnO_2 gives a net gain of about 18 W/m².

The relative performance of the different windows shown in Figure 5 is somewhat surprising considering Figure 4 and Table 1, which show the relatively low transmittance of the SnO_2 layers and the higher transmittance of the triple layers. This behaviour is explained, however, in Figure 6 and Figure 7. The first of these two figures presents how the temperature of the inner glass increases with the intensity of the incoming solar radiation. The temperature is obviously highest for the most absorbing panes. When the temperature of the glass increases, the heat losses from the room to the inner glass are decreased. At a high enough solar radiation, the glass temperature will reach room temperature and the heat-transfer will change direction. The net effect of the increased temperature of the inner glass on the heat-transfer is shown in Figure 7. This figure presents the detailed heat-transfer for an SnO_2 coating on the

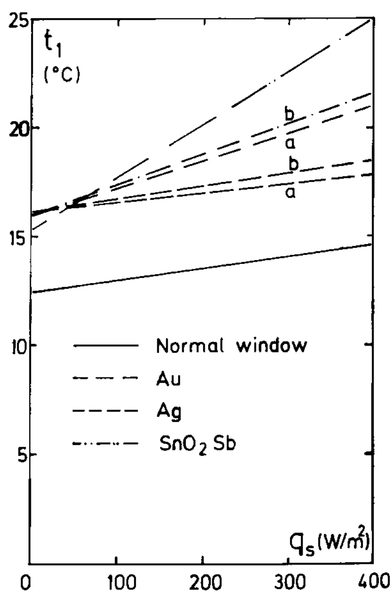

Figure 6. The temperature of the inner glass as a function of insolation. The outside of the glass coated as indicated. Metal- and ZnS-thicknesses as in Figure 4.

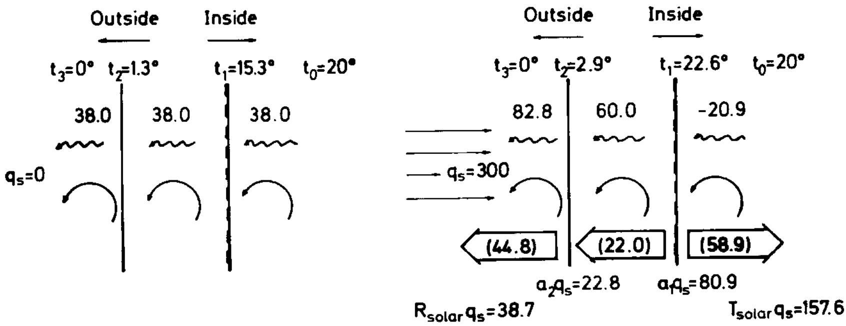

Figure 7. The solar transmittance, solar absorptance, and heat transfer for a coated window under darkness and insolation q_s = 300 W/m². The values in the arrow-shaped frames are differences between the two cases.

outside of the inner glass, assuming an insolation of 300 W/m². 52.5 percent of this solar radiation, or 157.6 W/m², is directly transmitted, and 27 percent, or 80.9 W/m², is absorbed by the inner glass. This absorbed radiation heats the inner glass to a temperature slightly above that of the room, and the heat flow of 38.0 W/m² *from* the room, in the case of non-absorbing coatings, is exchanged by a flow of 20.9 W/m² *to* the room, i.e., the absorption of 80.9 W/m² in the coating changes the heat flow 58.9 W/m². Consequently, 70 percent of the absorbed radiation-energy is turned into useful heat.

We found this fraction to be almost independent of the emittance of the coating. We can, therefore, in a practical analysis, use the following ad hoc formula for the resulting heat-flow through a window:

$$H_t = 1 - H_r - 0.3\ H_a$$

where H_r is the reflected and H_a the absorbed fraction of the solar radiation. If there is a choice between low solar reflectance and absorption, a low reflectance value is preferred.

If the layers in Figure 4 are compared as coatings on the inner glass for the purpose of maximum energy-transfer, the effect of the absorptance mentioned above will be considerable. Figure 8 is derived from Figure 4, assuming that 70 percent of the absorptance in the film can be added to the transmittance as contributing to the transfer of usable energy through the coated pane. This strongly affects the relative positions of the coatings in the diagram. Shown in this figure are also metallic Cu films and ZnS/Cu/ZnS layers which have comparable properties with the other noble-metal based layers. The data for the Cu films necessary to

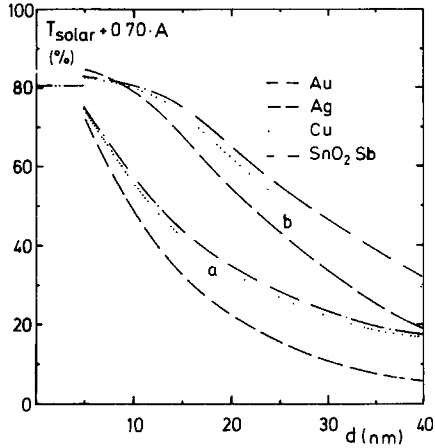

Figure 8. The effective transmission, T + 0.70 x A, of metals, triple-layers and the SnO_2-film. a: Single metal. b: ZnS/M/ZnS.

evaluate the results in Figure 8 were taken from reference [17] like the data for Au and Ag. The SnO_2 which exhibits high absorptance, but a moderate reflectance, is considerably increased in merit compared to the metal-based coatings. It underlines further, as noted above, that it is more important to lower the reflectance of the SnO_2-layer than to decrease the aborptance. Since the reflectance of the oxide is inherently determined by its refractive index, it can only be lowered by an anti-reflection coating or by adjusting the interference-minima to the middle of the solar spectrum.

Generally, Ag has been assumed as preferable in applications where maximum transmission is desired [22]. This is connected to its very low internal absorptance in the visible wavelength region. Ag is also superior compared to other metals when a narrow high transmission peak in the visible is desired [23]. Figure 4 shows, however, that when the integrated transmittance over the broad solar-spectrum is desired, Au is better than Ag except for very thin films. This tendency is enhanced in Figure 8 where the retransfer of heat is taken into consideration. Both Au and Cu show considerably higher effective transmittance than Ag. This effect is also shown in Figure 9, which gives the totally transmitted energy to the room versus metal film thickness for the bare metal coatings or triple layers. The figure shows that Au coatings are better than the corresponding Ag coatings except for very thin films, which hardly can be realized in practice. The SnO_2 films are better than the metal films thicker than 13 nm.

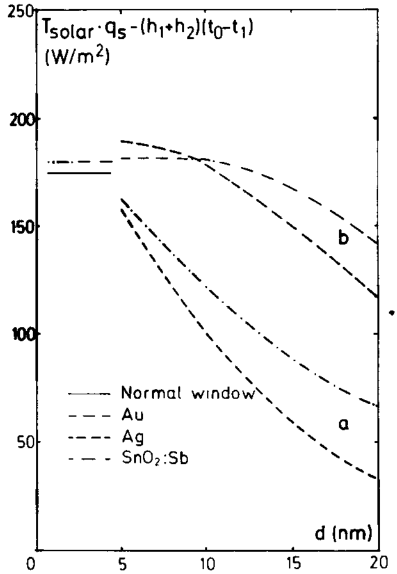

Figure 9. The net energy flow through a window as a function of metal thickness for Ag, Au and triple layers. Compared to a SnO_2-coated and a normal window under insolation q_s = 300 W/m². a: Single metal. b: ZnS/M/ZnS.

This important effect of the absorbed heat is of course not obtained if the coating is applied on the outer glass. In this case, the forced convection of the wind will effectively cool the glass and prevent the absorbed heat to reach the room. This means, that, if a sun screening effect is desired, the coating should be applied on the inner surface of the outer glass.

CONCLUSIONS

In this report, we have studied the heat-flow through a double-glazed domestic window with three different types of low-emitting coatings: noble metal films; multilayers ZnS/noble metal/ZnS; and the wide band-gap semiconductor SnO_2.

A substantial reduction in the dark U_L-value can be obtained with a single noble metal film on one of the surfaces facing the air-gap.

When insolation is considered, the higher solar transmission of the two latter types of filters is an important advantage. In our multi-layer calculations, the absorption in the dielectric has been neglected, but the absorption in the metal films was explicitly taken into account. It is found that about 70 percent of the absorbed energy is turned into useful heat. The commonly accepted prescription that silver is the best choice as metal in the metal based multilayers is, therefore, not valid when the total energy flow is considered. The fact that most of the absorption in gold adds to the total heat flux, makes it an equally good or even better choice than silver.

Although our calculations for SnO_2 are based on experimental values for films that have not been optimized for energy conservation, we find that this coating has the best performance. The absorption in the film causes only a small reduction in the solar heat transport. The most important factor is the low visible reflectance compared to the noble metals. The SnO_2 coating gives a higher net energy transfer to the room than the naked window for a solar radiation intensity up to 320 W/m².

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