Heat gain through transparent walls

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PREFACE

The contemporary trend to large areas of glass in the outside walls of buildings has resulted in very substantial increases in the air conditioning requirements of these buildings. In some cases, the cost of the extra cooling capacity necessitated by the use of glass walls is twice as much as the cost of the glass itself. It is, therefore, very important to be able to calculate accurately the cooling loads of buildings with glass curtain walls or large window areas.

This paper by Salvatore Martorana contains a lucid summary of the heat transfer phenomena that occur in a glass wall that is exposed to solar radiation. It includes, as an example, an analysis of the reduction in heat gain that can be achieved by using blinds and heat absorbing glass. The example is for a building in Rome, but the results are pertinent for southern Ontario and the northern states of the United States. This paper has been translated into English in the hope that it will help to propagate to the building designers in the English-speaking countries the importance of solar heat gain in building design.

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HEAT GAIN THROUGH TRANSPARENT WALLS

General

The estimation of heat gain through transparent walls has been the subject, in recent years, of considerable theoretical and experimental research.

The most complete investigations for purposes of calculation are the ones described in the ASHRAE Guide and the one reported by Desplanches in the second volume of the AICVF Guide. However, the data of these two guides are inadequate when it is desired to extend their use to cases differing from the ones considered either for the characteristics of the wall or for the climatic conditions.

This is not unexpected in our regions where the supplies of heat can be large even in autumn and winter (Fig. 1).

On the other hand the complexity of the various formulae proposed and the difficulty of locating the values of the coefficients in the common manuals make it impossible to deal with such cases with the required dispatch.

These considerations have led to a rearrangement of the more significant theoretical and experimental material and to the derivation of tables and equations with which most of the technical problems can be easily solved.

The most convenient scheme of calculation appears to be that indicated in Fig. 2, which can be extended to more complex walls and which is the one most commonly used; let us illustrate briefly.

On the wall, I_D is the intensity of the direct solar radiation and I_d that of the diffuse radiation, both known; of these, the transmitted component is

$$I\tau = \tau_D I_D + \tau_d I_d, \tag{1}$$

the absorbed component

$$I_a = a_D I_D + a_d I_d \tag{2}$$

the reflected component

$$I_r = r_D I_D + r_d I_d \tag{3}$$

where τ_D and τ_d, a_d, r_D and r_d are the transmission, absorption and total reflection factors of the wall for direct and diffuse radiation.

The transmitted component is transformed into heat on the furnishings and inside surfaces of the room, so that it always represents a positive heat supply.

The absorbed component is transformed into heat within the wall itself, which gives it up by convection and radiation either to the internal or external environment or both.

Thus, the calculation of the heat gain requires a knowledge of the factors defined above for the various walls and a knowledge of the heat transmission relationships which permit estimation of the quantity of heat Q_i and Q_e exchanged by the wall with the two environments.

Transmission of Radiation

Direct radiation

The transmission of direct radiation through any wall made up of several absorbing layers, has been dealt with by Professor Bozza in a monograph of 1935[1], which has not to this day been superseded.

From the normal incidence he determined the course of radiation in the interior of the wall, assuming that this radiation is monochromatic, is reflected several times on the surfaces of separation of the different layers and that it is absorbed in these layers according to an exponential law.

The formulae obtained, extended to oblique incidence and suitably modified, lend themselves well to the calculation of the transmission, absorption and total reflection factors of a large number of transparent walls.

For the most common of these, comprising one or more panes of glass separated by a thin air gap, the expressions for the above factors are as follows: for a wall consisting of one pane

$$\tau_D = \frac{(1 - \rho)^2 \exp\left(- \frac{ks}{\cos r}\right)}{1 - \rho^2 \exp\left(- \frac{2ks}{\cos r}\right)}$$

$$r_D = \rho + \frac{(1 - \rho)^2 \rho \exp\left(- \frac{2ks}{\cos r}\right)}{1 - \rho^2 \exp\left(- \frac{2ks}{\cos r}\right)} \qquad (4)$$

$$a_D = 1 - (\tau_D + r_D)$$

for a wall consisting of two panes

$$\tau_D = \frac{\tau_{De}\tau_{Di}}{(1 - \rho^2)\Delta}$$

$$r_D = \rho + \rho \left[p_e + \frac{\tau_{De}^{\,2}}{(1 - \rho^2)\Delta} (1 + p_i)\right]$$

$$a_{De} = 1 - \left[\tau_{De} \frac{1 - \rho(1 + p_i)}{(1 - \rho^2)\Delta} + r_D\right] \qquad (5)$$

$$a_{Di} = 1 - (\tau_D + r_D + a_{De})$$

$$\Delta = \left(1 - \frac{\rho^2}{1-\rho^2} p_e\right) \left(1 - \frac{\rho^2}{1-\rho^2} p_i\right) - \frac{\rho^2}{(1-\rho^2)^2} p_e p_i$$

$$p_e = \tau_{De} \exp \left(- \frac{k_e s_e}{\cos r}\right) \quad p_i = \tau_{Di} \exp \left(- \frac{k_i s_i}{\cos r}\right)$$

where s is the thickness of the pane, a is the absorption coefficient of the glass, ρ is the air-glass reflection factor and r is the angle of refraction; the subscripts "e" and "i" refer respectively to the first and last pane.

The absorption coefficient of glass depends on the ambient temperature, the chemical composition of the glass and the wavelength of the incident radiation.

For ordinary glasses its values are low in the visible range, of the order of 10 - 15 m^{-1}, and increase rapidly in the violet direction and less rapidly in the red end of the spectrum; above 4.5 - 5μ, for which it is 800 - 1500 m^{-1}, ordinary glass of the usual thickness is practically opaque(2).

The variations of the coefficient of absorption with the wavelength have been exploited by the glass industry to produce glasses capable of reducing the access of heat and limiting the luminence of windows. Such glasses, called athermic, are particularly absorbent in the infrared region and fairly absorbent in the visible.

Figure 3 shows clearly how the two types of glass vary the spectral distribution of solar radiation.

The absorption coefficient of the more common glasses on the Italian market, relative to the solar spectrum at sea level and air mass equal to 2 as proposed by P. Moon(3), has an average value of 20 - 22 m^{-1} for ordinary glasses and 108 - 112 m^{-1} for athermic glasses, which is about the same as the corresponding glasses produced in France(4) and in America(5).

For technological reasons these values can vary by 4 to 5% for ordinary glasses and 8 to 12% for athermic glasses. Less easily estimated, however, are the variations associated with the solar spectrum. Just the reddening of Moon's spectrum, caused by the increase of the air mass from 2 to 5, reduces the transparency for normal incidence over a thickness of 6 mm by 1 - 2% for the ordinary glasses and 7 - 8% for the athermic ones.

The reflection factor depends on the angle of incidence, the wavelength of the incident radiation, its state of polarization and the absorption coefficient.

At ambient temperature, for ordinary and athermic glasses, the variations with the coefficient of absorption are negligible; thus, where n is the index of refraction and i the angle of incidence, the reflection factor can be expressed by the simplified relationship

$$\rho = \left(\frac{n - 1}{n + 1}\right)^2$$

for normal incidence, (6)

$$\rho = \tfrac{1}{2}\,(\rho' + \rho'')$$

for oblique incidence;

where $\rho' = \dfrac{\sin^2(i - r)}{\sin^2(i + r)}$ is the reflection factor for the radiation component polarized in the plane of incidence, $\rho'' = \dfrac{\tan^2(i - r)}{\tan^2(i + r)}$ is the reflection factor for the radiation component polarized in the plane perpendicular to the plane of incidence, and r is equal to $\sin^{-1}\dfrac{\sin i}{n}$.

Table I gives the angles of refraction and the reflection factors at various angles of incidence calculated with a mean index of refraction of 1.52 for the solar spectrum[6].

From the values of ρ' and ρ'' it is clear that the reflection factors ρ can vary widely depending on whether one or the other component predominates. This happens either when the incident radiation is partially polarized, as is often the case for solar radiation, or after the first reflection in the case of oblique incidence, because the incident radiation is polarized and the transmitted radiation is further polarized at each reflection of the polarized component in the plane perpendicular to the plane of incidence.

Actually knowing the state of polarization of the solar radiation does not permit an estimation of the true variations of the reflection factors, and hence of the transmission factors. Comparison of the values of the latter for natural radiation and for the two linearly polarized components as given in Table II, suggests that in practice we can expect to find considerable oscillations around the mean value.

Polarization by reflection, however, has the effect of progressively diminishing the reflection factors for any given incidence. In order to take this fact into account the transmission factors are calculated as the mean values of those assumed for the two linearly polarized components.

Considerable variations in the reflection factors must also be attributed to the heterogeneity of the surface state of the glasses.

The above expressions can also be used in the common case where the wall is furnished with curtains for the control of the solar radiation. However, it is preferable in practice to derive this from the other more general formulae.

For this puprose note that curtains are devices for intercepting direct radiation, to which, therefore, they are opaque, and to control the transmission of the luminous flux, and hence also the diffuse radiation, to which they may be considered partially transparent. Their surfaces are in general partially diffusing[7].

Of the intercepted radiation a portion is reflected and a portion is absorbed and transformed into heat either outside or inside or within the wall, depending on whether the curtains are located outside or inside, or are incorporated in the wall itself. In the latter arrangement the reflected energy, before retraversing the glass, is reflected and absorbed a number of times by the glass panes and by the curtains.

We are not far wrong, therefore, in assuming that the curtains are opaque to the direct and diffuse radiations and that the transmission occurs according to the mechanism represented in Fig. 4, where for convenience the intensity of the incident radiation is assumed equal to unity and the wall is assumed to consist of two panes with an inside curtain.

On this basis, since the curtain receives the radiation τ_D in addition to the group of radiations Rr_d reflected by the glass panes and returns the radiation R to the glass while absorbing and transforming the fraction τ_D' into heat, which for this situation coincides with the transmission factor, we may write

$$\tau_D' = (\tau_D + Rr_d)a$$

$$R = (\tau_D + Rr_d)(1 - a),$$

where a is the absorption factor of the curtain.

Now, solving the system and observing that the outside glass and the inside glass respectively absorb the fraction a_{De} and a_{Di} of the incident radiation as well as the fractions Ra_{di} and Ra_{de} of R, and that two glasses reflect the fraction r_D of the former and transmit the fraction $R\tau_d$ of the latter, we derive the desired relationships

$$\begin{aligned} \tau_D' &= \tau_D \frac{a}{1 - r_d(1 - a)} \\ a_{De}' &= a_{De} + Ra_{di} \\ a_{Di}' &= a_{Di} + Ra_{de} \\ r_D' &= r_D + R\tau_d \\ R &= \tau_D \frac{1 - a}{1 - r_d(1 - a)}, \end{aligned} \qquad (7)$$

where a_{De}', a_{Di}' and r_D' are respectively the absorption factors for the outside glass, the inside glass and the total reflection factor.

Equation (7) holds also for walls consisting of a single pane where the magnitudes which appear there are replaced by those corresponding to the single pane and the absorption factors are put equal to 0 and to a_D', respectively.

For walls with curtains incorporated between the two panes $a_{De}' = a_D'$, $a_{Di}' = 0$, $\tau_D' = a_{Dc}'$; in this case the energy absorbed by the curtain is transformed into heat within the walls and not within the walls and not within the room.

If the curtains are external it is obvious that they absorb the fraction a of the energy of incident unit intensity and do not reflect the fraction 1-a.

Finally, we note that the relations obtained hold strictly for parallel curtains very close to the glass panes, i.e. for conditions of maximum efficiency.

Diffuse radiation

The transmission of the diffuse radiation can be dealt with very simply by imagining that the radiation impinges on the wall from all directions contained within the solid angle 2π with intensity distributed either uniformly or according to Lambert's law.

In the first case the transmission, absorption and reflection factors are given by the arithmetic mean of the values which each of these have between 0 and $\pi/2$ for direct radiation; in the second case, however, they are given by the weighted means of these values in which the weights are the radiation intensities at each angle of incidence.

We have based our calculations, the results of which we shall present below, on the latter hypothesis, which appeared physically more reliable.

In practice, the overhangs of the façade reduce the above-mentioned solid angle. However, even with a cone angle restricted to 150 - 160°, this makes less than 1% difference in the result and is therefore negligible.

The distribution of incident energy in the solid angles under consideration, assumed unitary, was found to be as follows:

Solid angle	Energy
0 - 10°	0.03015
10 - 20°	0.08682
20 - 30°	0.13303
30 - 40°	0.16318
40 - 50°	0.17364
50 - 60°	0.16318
60 - 70°	0.13303
70 - 80°	0.08682
80 - 90°	0.03015

Thus 76.6% of this energy is found within the solid angle between 20 and 70°.

Hence the difficulty of protecting the wall from diffuse radiation and of estimating the fraction intercepted by various protective devices with a single value.

Venetian blinds, close to the glass and with the vanes turned so as to produce integral reflection of the direct radiation*, in general intercept ½ - ⅓ of the diffuse radiation, i.e. all or part of that coming from above.

The transmission of the intercepted fraction through walls with curtains can again be investigated with the aid of equation (7) where the transmission, absorption and total reflection factors are now those relative to the diffuse radiation.

Experimental results and practical values for the transmission, absorption and reflection factors

The mentioned investigation carried out in the ASHRAE laboratory in Cleveland, Ohio, seems to be among the most suitable for testing the reliability of the calculations that can be carried out with the equations and methods that have been described.

In Table III are shown, for a glass with $ks \sim 0.05$ and $n = 1.52$, the values calculated by us and those published on page 312 of the ASHRAE Guide, 1957.

The agreement, as is apparent, is extremely good. If we had neglected the polarization due to reflection the theoretical values for the transmission factors would have been smaller from 40 - 50° or by 3 - 5% for the wall made of single glass and 8 - 10% for th t consisting of two panes.

Encouraged by this result we have calculated and present in Table IV the transmission and absorption factors and the total reflection factors for direct and diffuse radiation for the main combinations that can be realized with the more common ordinary and athermic glasses obtainable in the Italian market, and with curtains having an absorption factor equal to 0.5.

The latter depends, as is known(7), on the colour of the curtain so that when considerable variations are foreseen with respect to the assumed value it will be necessary to take these into account with correction factors that can be derived from equation (7).

For the walls with curtains the data of the table are applied to the direct and diffuse radiation fractions which are presumed intercepted.

Translator's Note:

* This probably means that the blind is adjusted to intercept all of the direct solar beam.

Heat Transmission

Basic relations

The transmission of heat by convection, conduction and radiation between two environments at different temperatures, separated by a wall in the interior of which heat is generated according to some law, has been treated several times by rigorous methods.

These methods, however, have not been widely used in our case because the uncertainties inherent in the very nature of the problem with which we are concerned are so great that recourse to very refined calculations is not justified, and because the frequency with which the problem comes up in engineering offices renders it preferable to employ approximate and rapid solutions.

In an attempt to reconcile scientific precision with rapidity of calculation Desplanches has recently proposed[4] a study of heat transmission under the above conditions, assuming infinte thermal conductivity of the glass and uniform distribution of the heat generated in the interior of the wall.

The two hypotheses, which for practical purposes do not change the final results in view of the small thickness of the glass panes, are both useful. The second however is too restrictive, because when the wall consists of several panes of different absorption characteristics we cannot assume uniform distribution of heat and in fact Desplanches applies the method to a wall comprising only one pane or two non-absorbing panes.

When we wish to study the behaviour of walls made with panes of different absorption, it will be necessary to restrict the hypotheses to each pane; in this way, the method retains all its good qualities.

On this basis let us consider a wall (Fig. 5) comprising three panes of infinite thermal conductivity, in which is generated the quantity of heat q_e, q_c and q_i; let t_e and t_i be the temperatures of the two environments, ϑ_e, ϑ_c and ϑ_i the temperatures of the panes and α_e, α_i, α_{ce}, α_{ci} the coefficients of heat transfer.

Now, choosing any condition of regime, for example $t_c < \vartheta_e < \vartheta_c > \vartheta_i > t_i$, we may write

$$q_e + q_c + q_i = \alpha_i(\vartheta_i - t_i) + \alpha_e(\vartheta_e - t_e)$$

$$q_c = \frac{\alpha_{ci}}{2}(\vartheta_c - \vartheta_i) + \frac{\alpha_{ce}}{2}(\vartheta_c - \vartheta_e) \tag{8}$$

$$q_i = \alpha_i(\vartheta_i - t_i) - \frac{\alpha_{ci}}{2}(\vartheta_c - \vartheta_i)$$

whence we derive

$$\vartheta_i = t_i + \frac{K}{\alpha_i}\left[\Delta t + \frac{q_e + q_c + q_i}{\alpha_e} + 2q_i\left(\frac{1}{\alpha_{ci}} + \frac{1}{\alpha_{ce}}\right) + 2\,\frac{q}{\alpha_{ce}}\right]$$

$$\vartheta_e = t_e + \frac{K}{\alpha_e}\left[-\,\Delta t + \frac{q_e + q_c + q_i}{\alpha_i} + 2q_e\left(\frac{1}{\alpha_{ci}} + \frac{1}{\alpha_{ce}}\right) + 2\,\frac{q_c}{\alpha_{ci}}\right] \qquad (9)$$

$$\vartheta_c = t_i + K\left(\frac{2}{\alpha_{ci}} + \frac{1}{\alpha_i}\right)\left[\Delta t + \frac{q_e + q_c + q_i}{\alpha_c} + 2q_i\left(\frac{1}{\alpha_{ci}} + \frac{1}{\alpha_{ce}}\right) + 2\,\frac{q_c}{\alpha_{ce}}\right] - 2\,\frac{q_i}{\alpha_{ci}}$$

where

$$K = \left[\frac{1}{\alpha_e} + \frac{1}{\alpha_i} + \frac{2}{\alpha_{ce}} + \frac{2}{\alpha_{ci}}\right]^{-1}$$

is the total coefficient of transmission and

$$\Delta t = (t_e - t_i)$$

is the temperature difference between the outside and inside environments.

The heat exchanged with the two environments is calculated as usual with

$$Q_i = \alpha_i(\vartheta_i - t_i)$$
$$Q_e = \alpha_e(\vartheta_e - t_e) \qquad (10)$$

which, taking into account equation (9), become

$$Q_i = K\left[\Delta t + \frac{q_e + q_c + q_i}{\alpha_e} + 2q_i\left(\frac{1}{\alpha_{ci}} + \frac{1}{\alpha_{ce}}\right) + 2\,\frac{q_c}{\alpha_{ce}}\right]$$
$$Q_e = K\left[-\Delta t + \frac{q_e + q_c + q_i}{\alpha_i} + 2q_e\left(\frac{1}{\alpha_{ci}} + \frac{1}{\alpha_{ce}}\right) + 2\,\frac{q_c}{\alpha_{ci}}\right]. \qquad (11)$$

The exchange of heat with the inside can be tabulated, if required; for this purpose the expression

$$Q_i = K(t_e{*} - t_i) \qquad (12)$$

is convenient, where

$$t_e{*} = t_e + \frac{q_e + q_c + q_i}{\alpha_e} + 2q_i\left(\frac{1}{\alpha_{ci}} + \frac{1}{\alpha_{ce}}\right) + 2\,\frac{q_c}{\alpha_{ce}}$$

is the "imaginary solar temperature".

For walls comprising two panes we put $q_c = 0$ and $\alpha_{ci} = \alpha_{ce} = 2\alpha_c$, and for that comprising one pane $q_c = q_i = 0$, $q_e = q$ and $\alpha_{ci} = \alpha_{ce} = \infty$.

None of the hypotheses presented was based on the regime which becomes stabilized in the wall; for the one comprising a single pane it is treated as a special regime which some heat engineers have defined as "permanent instantaneous regime". Since the thermal conductivity and hence the capacity for diffusion is infinite, the wall instantaneously assumes the regime temperature.

In practice ordinary glasses establish the regime in 5 - 10 minutes and athermic glasses in 15 - 20 minutes.

Application to a specific case and suggestions for calculation and for planning of walls

In Table V we have corrected the data and essential calculation results on the supplies of heat which will presumably be found in Rome on the 23rd of July at 4:00 p.m. through a number of transparent walls with western exposure, made of ordinary glass and of athermic glass and furnished with venetian blinds of painted aluminium.

The intensity of the direct solar radiation was derived from the sunshine tables edited by Termotecnica. The intensity of the diffuse radiation was obtained from Elvegard and Moericofer's curves[4]. The final value obtained, which is the annual maximum for Rome, may appear high, but it has to be accepted in the absence of more reliable data for the national territory than those correlated by Moon, as the extensors of this table, moreover, show.

In carrying out the calculation we tried to satisfy the condition at the boundaries of the various strata with a view to better estimating the interdependence of the different variables and the practical values of the heat transfer coefficient that can be used under similar conditions.

For natural convection we employed the correlations of Weise and Saunders[8], and for forced convection the correlations of Colburn[8], also adopted in the ASHRAE Guide, and for convection in the air gaps, those of Mull and Reiher[9] as verified and modified by Linke[10].

The first two correlations are taken with caution because they have been extrapolated up to surfaces of 2 m high, considered by us; more reliable, however, are the correlations of Linke who recently experimented on air gaps between glass with height/width ratios up to 112.

The outside heat transfer coefficient with a wind of 2.5 m/sec is almost always found to be equal to 15 kcal/m^2 hr°C; in cases no. 14 and 15 this reaches respectively 43 and 20 kcal/m^2 hr°C because to the convection is added in the first cast the irradiation of the outside glass, i.e. of a virtaully black body and in the second case the irradiation of the painted aluminium, i.e. a body of low emission capacity.

The inside heat transfer coefficient is generally 7 - 9 kcal/m^2 hr°C, except when the curtain is inside. In this case it may drop to 2 - 5.5 kcal/m^2 hr°C, because the glass gives up heat to the air by convection and receives heat from the curtains by irradiation.

In unventilated air gaps the thermal conductance is 15 - 18 kcal/m^2 hr°C. However, when the curtain is inside the gap this is reduced to 9 - 10 kcal/m^2 hr°C for the low emission capacity of the painted aluminium.

Unfortunately the temperatures are always high. Cold air against the glass is advantageous, because it reduces the temperature 3 - 5°C without appreciably increasing the heat gain.

In solutions concerned exclusively with glass these gains can be reduced by more than 50 - 60%. For greater reductions, in line with the general criterion that the solar radiation must be intercepted before reaching the surface of separation between the two environments, recourse must be had to inside curtains, curtains incorporated within the wall and outside curtains or curtains incorporated in ventilated air gaps.

In this regard the last column of the table, where the ratio C between the total heat transmitted by each wall and that transmitted under the same conditions by walls consisting of a single glass are recorded, is sufficiently indicative.

The curtains must be close to the glass, possibly flat, and must have a low absorption factor and high diffuse reflection factor, since glass is too transparent to this type of radiation. The regular reflection may reflect energy at angles for which glass is very reflective.

The emissivity of the curtains should, finally, be high. When the curtains are placed inside, however, low emissivity on the room side may be suitable.

The winter behaviour of the walls in question should be subjected to a similar investigation because they present some interesting aspects. For the present, however, the figures given are sufficient.

I wish to thank Professor Gino Bozza for his valuable suggestions made in the course of this study.

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Table I

Angles of refraction and air-glass reflection factors calculated for n = 1.52

i	r	ρ'	ρ"	ρ
0°	0°	—	—	0,04258
10°	6°35'	0,04358	0,04019	0,04188
20°	13°	0,05006	0,03573	0,04289
30°	19°10'	0,06170	0,02735	0,04452
40°	25°	0,08155	0,01561	0,04858
50°	30°15'	0,11756	0,00380	0,06068
56°40'	33°20'	0,15688	0	0,07844
60°	34°45'	0,18320	0,00153	0,09236
70°	38°10'	0,30815	0,04150	0,17482
80°	40°20'	0,54695	0,23543	0,39119
90°	41°10'	1	1	1

Table II

Transmission factors of glasses having ks ~ 0.05 for natural radiation (1) and for the linearly polarized components in the plane of incidence (2) and in the plane perpendicular to the plane of incidence (3)

Angles of incidence	One glass			Two glasses		
	1	2	3	1	2	3
0°	.875	.875	.875	.767	.767	.767
20°	.873	.860	.885	.765	.744	.786
40°	.861	.804	.918	.752	.660	.844
50°	.841	.745	.938	.729	.579	.879
60°	.794	.648	.939	.671	.459	.882
70°	.678	.491	.864	.527	.302	.751
80°	.419	.261	.576	.255	.127	.382

Table III

Values given in ASHRAE (1) and values calculated by us (2) of the transmission and absorption factors for walls comprising one or two glasses having ks ~ 0.05 and n = 1.52

Angles of incidence	One glass				Two glasses					
	τ_D		a_D		τ_D		a_{De}		a_{Di}	
	1	2	1	2	1	2	1	2	1	2
	Direct radiation									
0°	.87	.875	.05	.048	.76	.767	.06	.052	.04	.043
20°	.87	.873	.05	.049	.76	.765	.06	.053	.04	0.44
40°	.86	.861	.06	.053	.74	.752	.06	.056	.04	.046
50°	.84	.841	.06	.055	.72	.729	.07	.059	.05	.047
60°	.79	.794	.06	.057	.66	.671	.07	.063	.05	.048
70°	.67	.678	.06	.059	.52	.527	.07	.070	.05	.044
80°	.42	.419	.06	.059	.25	.255	.07	.077	.05	.034
	Diffuse radiation									
	τ_d		a_d		τ_d		a_{de}		a_{di}	
0° ÷ 90°	.79	.792	.06	.057	.68	.675	.07	.063	.05	.048

Table IV

Transmission, reflection and absorption factors of walls comprising ordinary glasses 5.50 mm thick, athermic glasses 6.35 mm thick and opaque curtains having an absorption factor equal to 0.5, calculated for solar radiation at sea level with air mass equal to 2

Make-up of the wall	Direct radiation, angles of incidence	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	Diffuse radiation 0° ÷ 90°	
Ordinary glass	τ_D	.818	.818	.815	.810	.800	.778	.731	.620	.375	0	τ_d	.734
	a_D	.109	.109	.111	.114	.119	.124	.129	.132	.128	0	a_d	.129
	r_D	.073	.073	.074	.076	.081	.098	.140	.218	.497	1	r_d	.137
Athermic glass	τ_D	.460	.459	.451	.440	.423	.399	.360	.292	.163	0	τ_d	.381
	a_D	.488	.489	.496	.506	.519	.531	.536	.517	.425	0	a_d	.533
	r_D	.052	.052	.053	.054	.058	.070	.104	.191	.412	1	r_d	.086
Two ordinary glasses separated by a thin layer of air	τ_D	.673	.673	.668	.660	.648	.623	.567	.438	.200	0	τ_d	.578
	a_{De}	.115	.115	.118	.122	.126	.133	.141	.151	.157	0	a_{de}	.139
	a_{Di}	.090	.090	.091	.093	.096	.098	.098	.089	.064	0	a_{di}	.098
	r_D	.122	.122	.123	.125	.130	.146	.194	.322	.579	1	r_d	.185
Ordinary glass outside and athermic glass inside, separated by a thin layer of air	τ_D	.377	.377	.369	.358	.342	.318	.278	.205	.084	0	τ_d	.302
	a_{De}	.113	.113	.116	.119	.124	.130	.138	.146	.150	0	a_{de}	.133
	a_{Di}	.402	.402	.406	.412	.418	.420	.405	.347	.207	0	a_{di}	.414
	r_D	.108	.108	.109	.111	.116	.132	.179	.302	.559	1	r_d	.151
Athermic glass outside and ordinary glass inside, separated by a thin layer of air	τ_D	.377	.377	.369	.358	.342	.318	.278	.205	.084	0	τ_d	.302
	a_{De}	.506	.506	.513	.523	.536	.549	.558	.548	.463	0	a_{de}	.553
	a_{Di}	.050	.050	.050	.051	.051	.050	.048	.041	.026	0	a_{di}	.049
	r_D	.067	.067	.068	.068	.071	.083	.116	.206	.427	1	r_d	.096
Ordinary glass and inside curtain	τ_D'	.439	.439	.437	.434	.429	.418	.392	.333	.201	0	τ_d'	.394
	a_D'	.165	.166	.168	.171	.174	.178	.180	.175	.154	0	a_d'	.180
	r_D'	.396	.395	.395	.395	.397	.404	.428	.492	.645	1	r_d'	.426
Athermic glass and inside curtain	τ_D'	.240	.240	.236	.230	.221	.208	.188	.153	.085	0	τ_d'	.199
	a_D'	.616	.617	.622	.629	.637	.642	.636	.598	.470	0	a_d'	.639
	r_D'	.144	.143	.142	.141	.142	.150	.176	.249	.445	1	r_d'	.162
Two ordinary glasses separated by a thin air gap, and inside curtain	τ_D'	.370	.371	.368	.364	.357	.343	.312	.241	.110	0	τ_d'	.319
	a_{De}'	.151	.152	.154	.157	.161	.166	.172	.175	.168	0	a_{de}'	.170
	a_{Di}'	.142	.142	.142	.144	.146	.146	.141	.123	.079	0	a_{di}'	.142
	r_D'	.337	.335	.336	.335	.336	.345	.375	.461	.643	1	r_d'	.369
Ordinary outside glass, athermic inside glass, separated by a thin air glass - inside curtain	τ_D'	.198	.198	.194	.188	.180	.167	.146	.108	.044	0	τ_d'	.158
	a_{De}'	.123	.123	.126	.129	.133	.138	.145	.151	.152	0	a_{de}'	.141
	a_{Di}'	.511	.512	.513	.516	.517	.512	.485	.407	.231	0	a_{di}'	.502
	r_D'	.168	.167	.167	.167	.170	.183	.224	.334	.573	1	r_d'	.199
Athermic glass outside, ordinary glass inside, separated by a thin air gap - inside curtain	τ_D'	.204	.204	.200	.194	.185	.172	.150	.111	.045	0	τ_d'	.163
	a_{De}'	.077	.077	.077	.076	.075	.073	.068	.056	.032	0	a_{de}'	.621
	a_{Di}'	.590	.591	.595	.603	.613	.620	.620	.593	.482	0	a_{di}'	.071
	r_D'	.129	.128	.128	.127	.127	.135	.162	.240	.441	1	r_d'	.145
Two ordinary glasses - curtain incorporated	τ_D'	0	0	0	0	0	0	0	0	0	0	τ_d'	0
	a_{De}'	.165	.166	.168	.171	.174	.178	.180	.175	.154	0	a_{de}'	.180
	a_{Dc}'	.439	.439	.437	.434	.429	.418	.392	.333	.201	0	a_{dc}'	.394
	a_{Di}'	0	0	0	0	0	0	0	0	0	0	a_{di}'	0
	r_D'	.396	.395	.395	.395	.397	.404	.428	.492	.645	1	r_d'	.426
Ordinary glass outside - athermic inside and curtain incorporated	τ_D'	0	0	0	0	0	0	0	0	0	0	τ_d'	0
	a_{De}'	.165	.166	.168	.171	.174	.178	.180	.175	.154	0	a_{de}'	.180
	a_{Dc}'	.439	.439	.437	.434	.429	.418	.392	.333	.201	0	a_{dc}'	.394
	a_{Di}'	0	0	0	0	0	0	0	0	0	0	a_{di}'	0
	r_D'	.396	.395	.395	.395	.397	.404	.428	.492	.645	1	r_d'	.426
Athermic glass outside, ordinary glass inside and curtain incorporated	τ_D'	0	0	0	0	0	0	0	0	0	0	τ_d'	0
	a_{De}'	.616	.617	.622	.629	.637	.642	.636	.598	.470	0	a_{de}'	.639
	a_{Dc}'	.240	.240	.236	.230	.221	.208	.188	.153	.085	0	a_{dc}'	.199
	a_{Di}'	0	0	0	0	0	0	0	0	0	0	a_{di}'	0
	r_D'	.144	.143	.142	.141	.142	.150	.176	.249	.445	1	r_d'	.162

Table V

Principal results of calculation of supplies of heat through various types of transparent walls, carried out under the following conditions: latitude 41°55' N (Rome) western exposure - 23rd July, 4 p.m. - solar elevation 35°30' - solar azimuth of the wall 0° - angle of incidence 35°30' - direct radiation 550 kcal/m² hr, entirely intercepted by the curtain - diffuse radiation 90 kcal/m² hr, intercepted by one third of the curtain - mean outside air temperature against the glass 32°C and wind 2.5 m/sec - mean air temperature inside against the window 26°C, or 20°C at 1 m/sec - thickness ordinary glass 5.50 mm - thickness athermic glass 6.35 mm - distance glass-glass or glass-curtain 20 mm - height of walls 2 m - emissivity of glass 0.925 - venetian blind of painted aluminium with absorption factor of 0.5 - emissivity of painted aluminium 0.20 - emissivity of outside and inside environments, 1

Make-up of wall	t_i	I_τ	Q_i	$I_\tau+Q_i$	I_r	Q_e	I_r+Q_e	ϑ_i	ϑ_e	ϑ_c'	K	α_i	α_e	α_{ci}	α_c	α_{ce}	C
	°C	kcal/m²h						°C			kcal/m²h°C						
1 Ordinary glass	26	507	51	558	57	19	76	33,3			4,9	7,5	14,5				1
	20		81	588		6	63	31,5			4,7	7	14,5				
2 Athermic glass	26	271	151	422	39	177	216	43,8			5,4	8,5	15				0,76
	20		184	455		144	183	41,6			5,4	8,5	15				
3 Two ordinary glasses, non-ventilated air gap	26	408	73	481	90	69	159	35,1	36,8		3	8	14,5		15		0,86
	20		86	494		56	146	32,3	35,9		2,9	7	14,5		15		
4 Ordinary glass outside, athermic glass inside, non-ventilated air gap	26	217	204	421	79	140	219	48,7	41,3		3,3	9	15		16,5		0,75
	20		220	437		124	203	45,9	40,3		3.2	8,5	15		16		
5 Athermic glass outside, ordinary glass inside, non-ventilated air gap	26	217	114	331	48	261	309	39,4	49,4		3,3	8,5	15		16,5		0,59
	20		131	348		244	292	36,4	48,3		3,2	8	15		16,5		
6 Ordinary glass and inside curtain	20	293	24	317	239	86	325	37,9		53,3	1,8	2	15				0,57
	26		61	354		47	286	35,2		45,8	3,1	4	15				
7 Athermic glass and inside curtain	26	153	103	256	88	296	384	51,7		43,5	3,1	4	15				0,46
	20		145	298		254	342	49		35	3,7	5	15				

Continued

Table V - continued

	Make-up of wall	t_i	$I\tau$	Q_i	$I\tau+Q_i$	I_r	Q_r	I_r+Q_r	ϑ_i	ϑ_e	ϑ_c°	K	α_i	α_e	α_{ci}	α_c	α_{ce}	C
		°C	kcal/m²h						°C			kcal/m²h°C						
8	Two ordinary glasses, inside curtain, non-ventilated air gap	26	242	63	305	207	128	335	44	40,5	51	2,1	3,5	15		16		0,55
		20		82	324		110	317	40,5	39,3	47,6	2,3	4	15		16		
9	Ordinary glass outside, athermic glass inside, inside curtain, non-ventilated air gap	26	124	183	307	108	225	333	62,6	47	42,4	2,6	5	15		18		0,55
		20		211	335		197	305	58,4	45,1	35,4	2,7	5,5	15		17		
10	Athermic glass outside, ordinary glass inside, inside curtain, non-ventilated air gap	26	127	99	226	80	334	414	48	54,3	41,5	2,5	4,5	15		17,5		0,40
		20		121	248		312	392	44,2	52,8	33,7	2,6	5	15		17		
11	Two ordinary glasses, incorporated curtain, non-ventilated air gap	26	35	143	178	241	221	462	41,9	46,7	69,5	1,75	9	15	10		10	0,32
		20		149	184		215	456	38,6	46,3	67,7	1,7	8	15	10		10	
12	Ordinary glass outside, athermic glass inside, incorporated curtain, non-ventilated air gap	26	18	159	177	239	224	463	43,7	46,9	70,5	1,75	9	15	10		10	0,32
		20		164	182		219	458	40,5	46,6	68,7	1,7	8	15	10		10	
13	Athermic glass outside, ordinary glass inside, incorporated curtain, non-ventilated air gap	26	18	114	132	91	417	508	39,4	59,8	62,6	1,65	8,5	15	9,5		9,5	0,24
		20		118	136		413	504	35,8	59,6	59,9	1,55	7,5	15	9		9	

Continued

Table V - continued

	Make-up of wall	t_i	I_τ	Q_i	$I_\tau+Q_i$	I_r	Q_e	I_r+Q_e	ϑ_i	ϑ_e	ϑ_c°	K	α_i	α_e	α_{ci}	α_c	α_{ce}	C
		°C	kcal/m²h						°C			kcal/m²h°C						
14	Athermic glass outside, ordinary glass inside, air current in gap 1 m/sec	26	217	41	258	48	342*	390	31,8	45,4		6	7	43				0,46
15	Two ordinary glasses, incorporated curtain, air current in gap 1 m/sec	26	35	33	68	211	358*	599	30,7	38,5	56,2	5,2	7	20				0,12
16	Ordinary glass outside, athermic glass inside, incorporated curtain, air current in gap 1 m/sec	26	18	38	56	239	358*	597	31,4	38,5	56,2	5,2	7	20				0,10
17	Athermic glass outside, ordinary glass inside, incorporated curtain, air current in gap 1 m/sec	26	18	29	47	91	528*	619	30,2	52	46,2	4,8	7	15				0,08
18	Ordinary glass, outside curtain, air current between glass and curtain 1 m/sec	26	47	30	77	291	294*	585	30,3		45	4,5	7	13				0,14
19	Two ordinary glasses, outside curtain, air current between glass and curtain 1 m/sec	26	38	22	60	292	295*	587	29,1	31,5	45	2,8	7	13		15		0,11

(o) ϑ_c indicates the temperature of the curtain, whether outside, inside or incorporated.
(*) This refers to the heat absorbed by the outside glass, curtain or both.

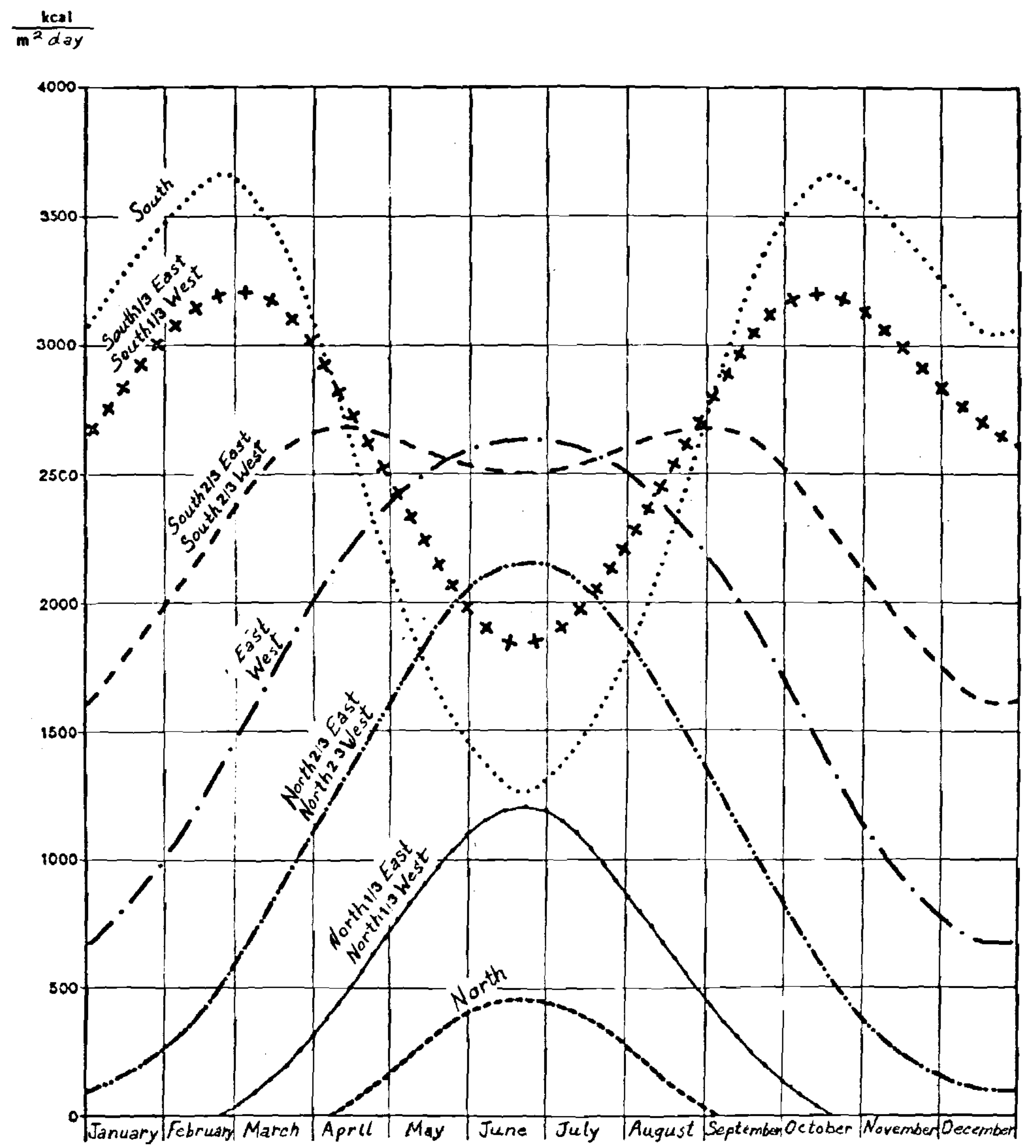

Fig. 1

Direct solar radiation striking vertical walls at the latitude 41°55'N (Rome) calculated from the sunshine table published by Termotecnica

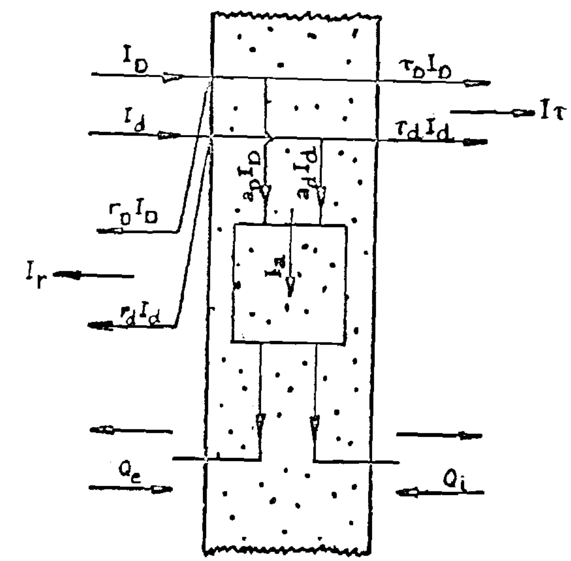

Fig. 2

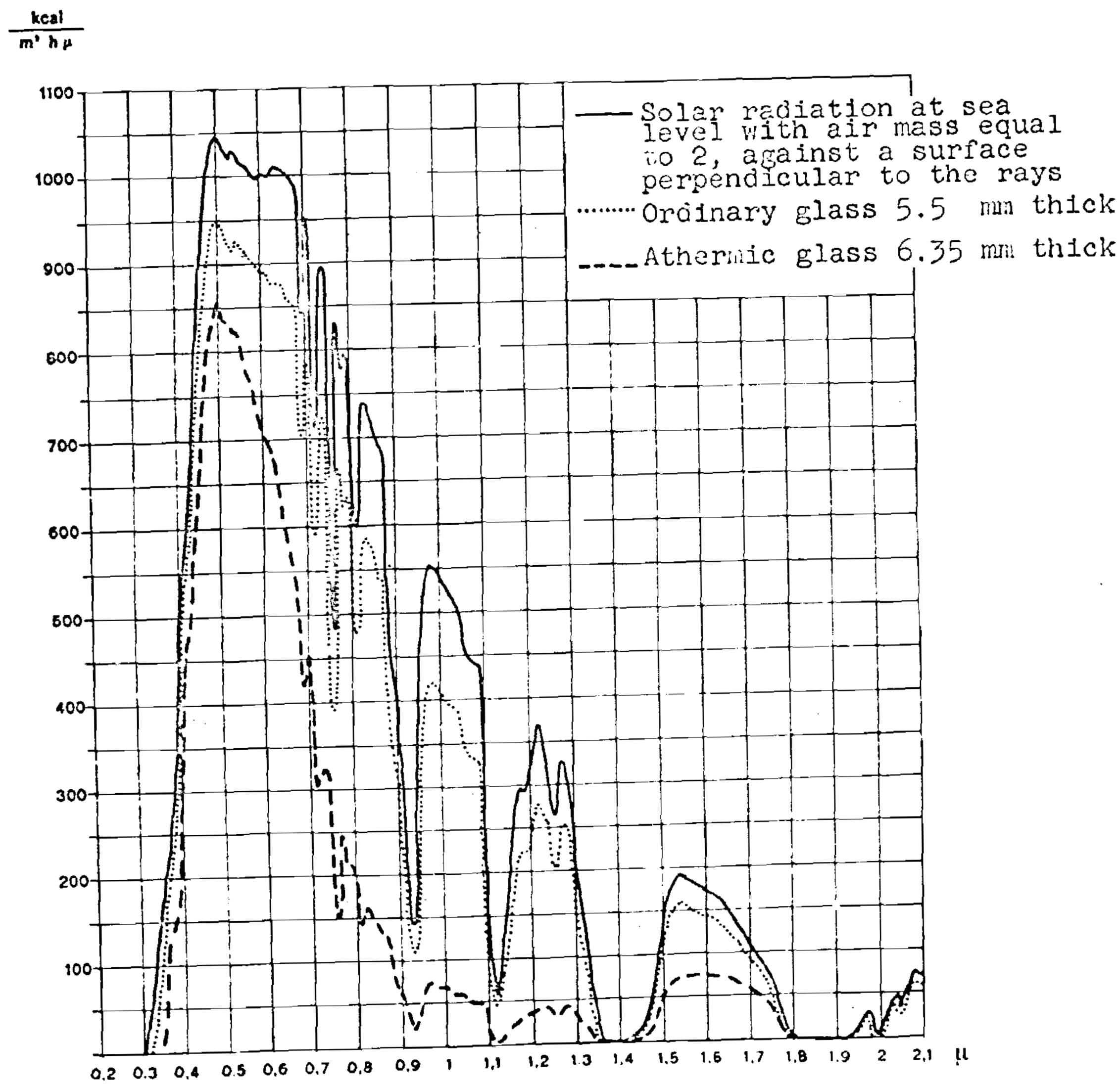

Fig. 3

Transmission of solar radiation with normal incidence through an ordinary glass and an athermic glass

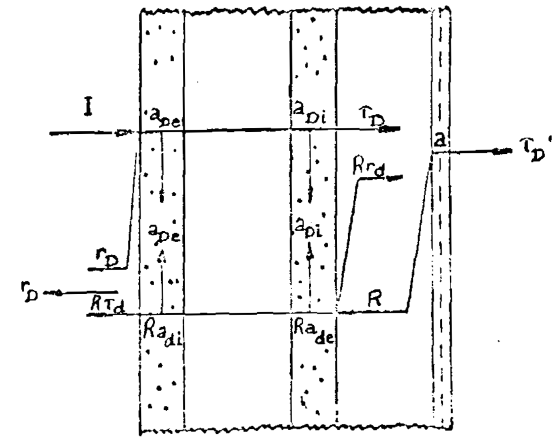

Fig. 4

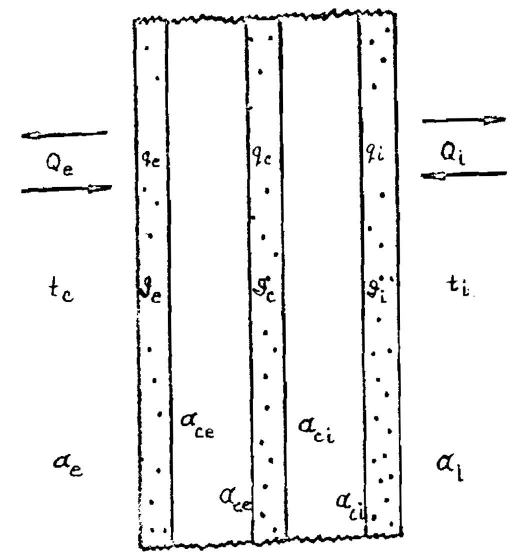

Fig. 5