note **6**

PLEA NOTES

Passive and Low Energy Architecture International
DESIGN TOOLS AND TECHNIQUES

KEEPING COOL

PRINCIPLES TO AVOID OVERHEATING IN BUILDINGS

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KEEPING COOL

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PREFACE

It is more than a year since the last PLEA Note (Note 5: Climate analysis) has been published. The new tax regulations in Australia prevent us (and the University of Queensland) in continuing the publication as we did. Fortunately Professor Ballinger, through his company: *Research, Consulting and Communication* was able and willing to take over the role of publisher (and found the new printer), while I am carrying on as editor.

It seems that there is an abundance of literature on bioclimatic or passive design and energy conservation for temperate climates (Europe and North America), but not so for warm and hot climates. For this reason we intend to devote the next few Notes to the problems of warm and hot climates.

In order to keep continuity, I repeat my invitation to readers to

1) suggest topics which could and should be tackled by future PLEA Notes
2) volunteer and offer to contribute such further material, which I will be glad to edit and arrange for publication.

The five Notes published so far, when looked at together, seem to constitute quite a respectable reference or learning set. Let us hope that we can keep up the good work and possibly improve on the relevance and quality of future such Notes.

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February 2001

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CONTENTS

INTRODUCTION

In low latitude warm regions the prevention of heating of habitable spaces constitutes the first step towards achieving comfort conditions and energy economy.

High intensity solar radiation in tropical zones, in addition to high temperatures frequently causes discomfort and high energy use. This is why it is very important to minimize heat gain in buildings in warm climates or warm seasons of temperate climates.

Overheating (human thermal discomfort) is caused by high ambient air temperature and high internal building surface temperatures. This is the problem in non-air-conditioned buildings. In air conditioned buildings the heat gain may not cause overheating, but comfort can be achieved only at the expense of using large amounts of non-renewable energy. Heat gain can be reduced, thermal comfort ensured or efficiency of the cooling system can be improved by applying design principles, such as those presented in this Note.

This Note aims to contribute to the selection and application of design strategies and details which will prevent overheating of 'free running' buildings, conditioned by natural means.

Lack of consideration of the appropriate principles in the design may result in uncomfortable buildings, due to high interior temperatures, even in temperate climate locations. Inappropriate orientation, undesirable greenhouse effects, or strong internal heat generation, among others, may cause overheating and discomfort in locations where the maximum day temperature reaches the upper limit of comfort.

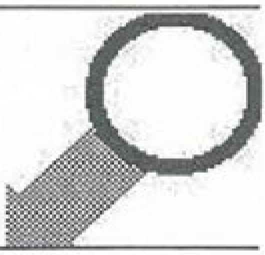
Treatment of the problem of overheating in buildings requires first of all, the clear identification of its causes. The methodology employed in this note is

- to analyse the variables which affect heat flows in building,
- to establish principles of design to prevent overheating,
- the main tool in this analysis is the thermal balance of the building, Ie. the consideration of heat and mass exchanges between the building and its environment.

MAIN HEAT FLOWS IN BUILDING

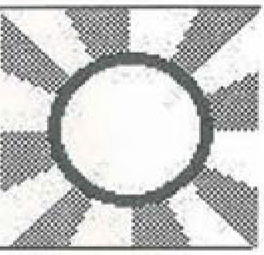
and their representative icons

1
beam (direct) solar radiation



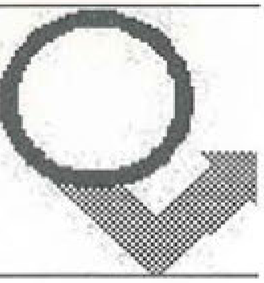
This is discussed on p.11 in general terms. Its effect on opaque elements is treated on p.11-13. Methods of protection (I.e. shading) are presented on p. 15-18.

2
diffuse solar radiation



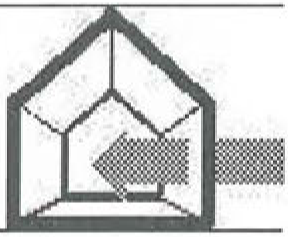
Definition is given on p.11. The sections listed above also deal with diffuse, together with beam (direct) solar radiation

3
reflected solar radiation



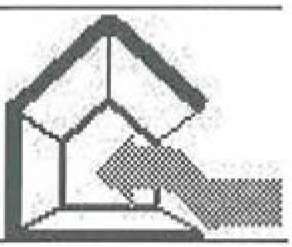
This is also mentioned on p. 11, but its main discussion is in chapter 4 (p.53-54)

4
envelope conduction



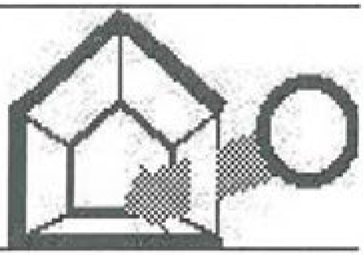
Heat conduction through the building envelope is analysed on p. 27-28. Section 3.2 (p.29-40) is devoted to the control of such heat flow by insulation and thermal capacitance.

5
ventilation



This is the subject of chapter 4 (p.41-48), including the strategies for opening and closing the building and the provisions for cross-ventilation (sensible velocities to provide physiological cooling)

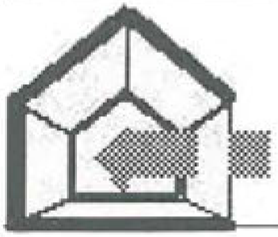
6
solar radiation through windows



The discussion of solar radiation through windows is included in chapter 2, especially in section 2.2 (p. 19-26), which includes the techniques for reducing solar effects by shading and special glasses.

7
ground heat conduction

This topic is included in chapter 3, but —as the main interest of this Note is warm-humid climates, where "earth coupling" is not very effective— it is not treated in depth.

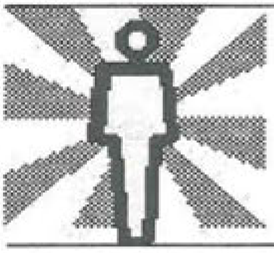


8
windows heat conduction

Windows are the most vulnerable elements of the envelope. This topic is included in chapter 3, especially p. 32-33 (Fig. 3.6), whilst insulating glasses are discussed on p. 25-26 of chapter 2.

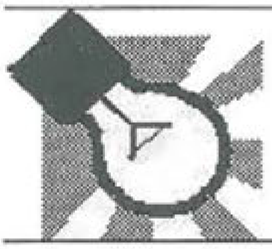
9
long wave radiation to sky

This is discussed on p. 12 (in conjunction with sol-air temperature) and also on p. 16-17, in conjunction with roof shading.



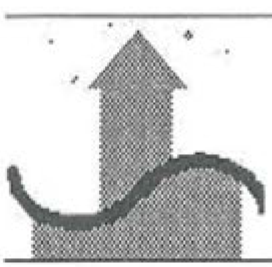
10
internal gain: occupants

This is the main subject of chapter 5, but it is also mentioned on p. 8-9



11
internal gain: electric light + appliances

Electric lighting and various appliances can be a large source of internal heat gain and are discussed in chapter 5 (p. 49-52).



12
evaporative cooling

This is not very effective in warm-humid climates, but it is mentioned on p. 7-9 for the sake of completeness. The evaporative cooling effect of vegetation is discussed in chapter 6 (p. 55-57).

SYMBOLS, UNITS AND ABBREVIATIONS

			discussed on p.
a	admittance	W/m²K	37-38
b	breadth, thickness	m	27
c	specific heat capacity	J/kg.K	41
gr	glazing ratio	---	22
h	surface conductance	W/m²K	12
ho	surface conductance, outside	W/m²K	12
hi	surface conductance, inside	W/m²K	12
i	angle of incidence	° or rad	11
q	building conductance	W/K	9
qc	envelope conductance	W/K	9
qv	ventilation conductance	W/K	9,41
sTi	swing in indoor temperature K		9
vr	ventilation (volume flow) rate	m³/s	8,9
A	area	m²	9
C	conductance	W/m²K	27
D	thermal inertia index	---	38
E	emitted energy density	W/m²	12
G	global solar irradiance	W/m²	
Gb	beam (direct) solar irradiance	W/m²	
Gbn	beam (direct) normal irradiance	W/m²	11
Gd	diffuse solar irradiance	W/m²	
Gr	reflected irradiance	W/m²	
GG	volumetric heat loss coefficient	W/m³K	14
H	irradiation	Wh/m² or J/ m²	
Hb	beam irradiation	Wh/m² or J/ m²	
Hd	diffuse irradiation	Wh/m² or J/ m²	11
Hr	reflected irradiation	Wh/m² or J/ m²	
N	number of air changes per hour	---	41
Q	density of heat flow rate	W	
Qc	conduction heat flow rate	W	
Qcv	convection heat flow rate	W	
Qev	evaporation heat flow rate	W	7
Qi	internal heat gain	W	
Qir	infrared radiation heat flow	W	
Qsw	solar heat flow: windows	W	
Qso	solar heat flow: opaque elements	W	
Qst	heat flow into/out of storage W		36
R	thermal resistance	m²K/W	27
Ra-a	air-to-air resistance	m²K/W	29
Rso	surface resistance, outside	m²K/W	29
Rsi	surface resistance, inside	m²K/W	29
SC	shading coefficient	---	23
SHGC	solar heat gain coefficient	---	24
SHGF	solar heat gain factor	---	13
Sg	glazed surface area	m²	22
St	total wall surface area	m²	22
S/V	surface to volume ratio	---	13
To	temperature outdoors	°C	9
Ti	temperature indoors	°C	9
Tsa	sol-air temperature	°C	12
U	thermal transmittance	W/m²K	29
V	volume	m³	14, 41
α	absorptance	---	18
α	thermal diffusivity	m²/s or m²/h	34
β	specific admittance (effusivity)		37
ε	emittance	---	18
η	efficiency	----	50
φ	time-lag	hour	34
λ	thermal conductivity	W/m.K	27
μ	decrement factor	---	34
θ	solar gain factor	---	19
ρ	density	kg/m³	34
ρ	reflectance	—	18, 25
τ	transmittance (optical)	---	19
ω	angular velocity		35

1 THERMAL EQUILIBRIUM IN BUILDINGS

The climate of a location is characterized by a set of meteorological variables that change in time and are interdependent. Buildings are exposed to these natural conditions and at the same time heat is generated in its interior, as a result of the metabolism of users, artificial lighting, electrical appliances, etc. Consequently, buildings are subject to dynamic thermal effects where heat transfer phenomena: radiation, conduction, convection, and mass transfer occur.

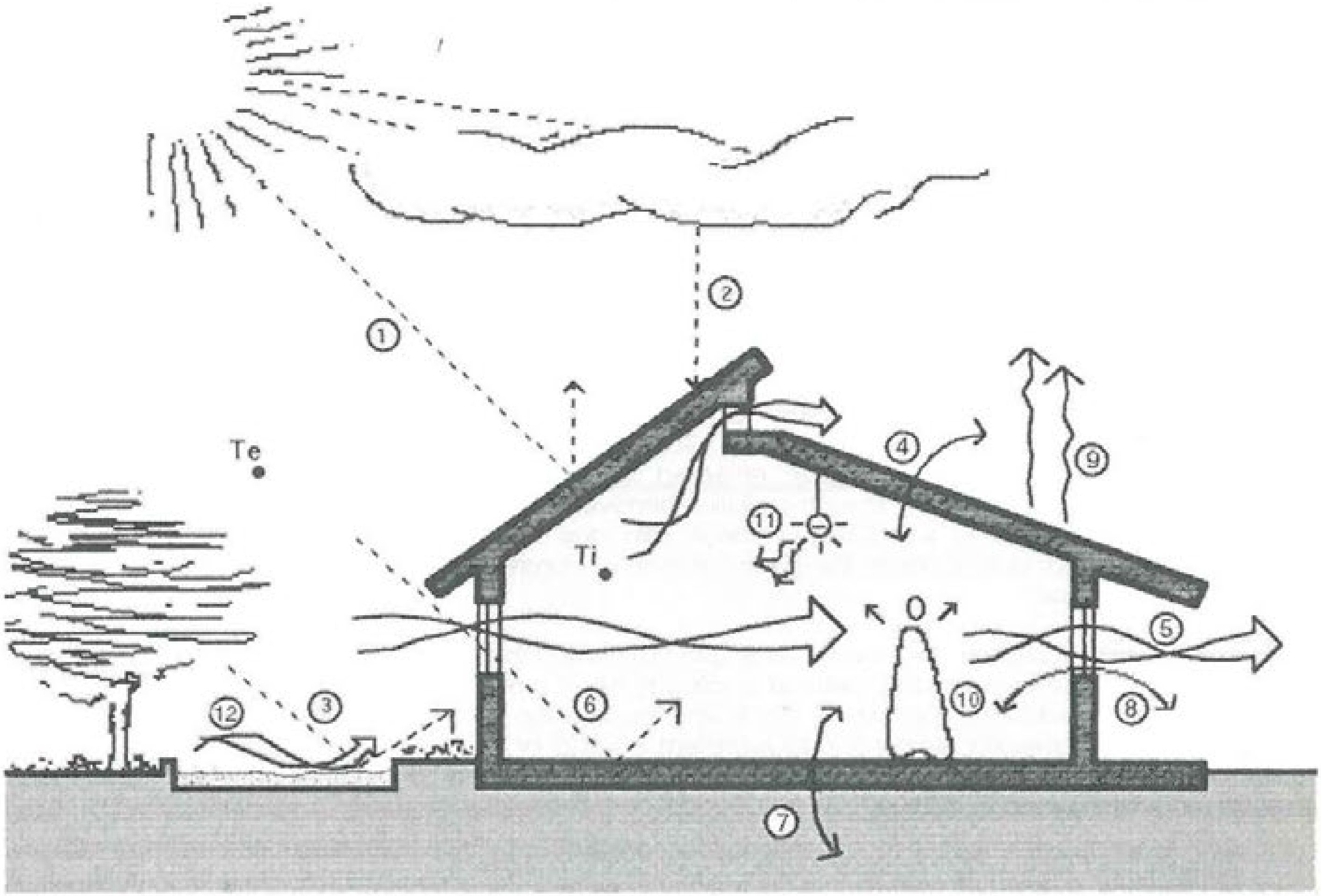


Fig. 1.1. Thermal exchanges between a building and the environment

1 Beam (direct) solar radiation
2 Diffuse solar radiation
3 Ground reflected solar radiation
4 Envelope heat conduction
5 Ventilation heat transfer
6 Window solar radiation
7 Ground heat conduction
8 Window heat conduction
9 Sky long wave radiation
10 Occupants heat contribution
11 Electric lights and appliances
12 Evaporative cooling

Analysis of the different heat flows affecting the thermal balance of a building permits the identification of components that can be modified to prevent overheating and improve thermal quality and energy efficiency of the building. Fig.1.1 shows the different flows of heat and the most important thermal phenomena that contribute to such balance.

From the energy and environmental point of view the ideal situation is when any need for artificial cooling is eliminated. For this case the heat balance equation, in a simplified form, (based on the 'superposition of steady and periodic thermal phenomena' - Lavigne, 1994) can be expressed as follows:

$$Qsw + Qso + Qi \pm Qc \pm Qcv - Qir - Qev = 0 \quad \text{... eq. 1.1)}$$

where (all terms are in units of W):

Qsw = solar heat flow transferred through windows (solar gain)
Qso = solar heat flow transferred through opaque surfaces
Qi = heat generated inside the building (internal gain)
Qc = conduction heat flow through envelope elements
Qcv = mass transfer heat flow: ventilation, infiltration
Qir = net long wave radiation heat flow
Qev = heat flow due to evaporation

In this equation all heat flows may be instantaneous, but are often considered as average values for a period (eg. 24 hours), in which case heat gains and losses represent the daily heating and cooling of the building. Conduction heat flow through the envelope (Qc) is the sum of the product of the transmittance (U-value) and area (A) of all envelope elements (often referred to as the envelope conductance of the building (qc = Σ(UA) in units of W/K) and the outdoor - indoor temperature difference (To - Ti). Heat transfer due to air mass exchange (Qcv) is the result of natural (or mechanical) ventilation, or air infiltration: vr · c · (To - Ti), that is, the product of air flow (vr = ventilation rate in m^3/s) and the volumetric specific heat of air (J/m^3K), often denoted qv, or ventilation conductance and the temperature difference, as above (note that if Ti >To, then To-Ti gives a negative result, ie a heat loss, whereas if Ti<To then the result is a heat gain.)

Radiant energy flow originating from the sun, can arrive at ground level in two forms: beam (or direct), (Gb) and diffuse (Gd) radiation, and a third component may be the radiation reflected by surrounding surfaces (Gr). As surfaces exposed to such radiation behave differently, for the purposes of analysis we distinguish heat gain due to solar radiation through opaque surfaces (Qso) and radiation transmitted through windows (Qsw).

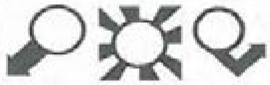
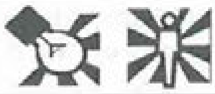
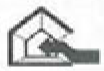
As a result of solar radiation and interior heat generation, the indoor average temperature of a building (without cooling systems) is higher than the average outdoor temperature. This is why, conduction heat flow through sun-protected elements can represent cooling or heat losses. As it will be further explained, a positive flow or heat gain results through surfaces exposed to the sun.

Heat flows Qir and Qev, which represent radiant long wave (infra-red) cooling and evaporative cooling, are not considered in this Note. They will, however, be the subject for study in further Notes of this series.

Table 1.1. shows a summary of the different heat flows present in a building, and the contributions or heat flows that should be prevented, controlled or promoted, in order to limit overheating of the interior of buildings.
This heat flow matrix of Table 1.1 and the general thermal balance equation (1.1) are the points of departure for the development of this Note. Each heat flow, as well as the principles for controlling these flows, are documented in the following chapters.

Considering temperatures, mass and heat flows as mean values of a 24 hour period, the average temperature difference between the interior and the exterior of a building (ΔTm, where 'm' indicates 'mean') can be expressed according to (eq. 1.1) as:

Table 1.1 Relations matrix of heat flows: principles to prevent overheating

Strategies /Heat Flows	Heat contributions to be prevented	Heat Contributions / Losses to be controlled	Heat losses to be promoted
Qsw			
Qso			
Qi			
Qc			
Qcv			
Qir			
Qev			

$$\Delta Tm = Tom - Tim = \frac{Qswm + Qsom + Qim + Qirm + Qevm}{qc + qv}$$ ... eq. 1.2)

where: $Tim = Tom + \Delta T$ ... eq. 1.3)

qc = $\Sigma(A \bullet U)$ = envelope conductance (W/K)
A = surface area of each envelope element (m^2)
U = transmittance of each element (W/m^2K)
qv = $vr \bullet c$ = ventilation conductance (W/K)
vr = ventilation rate (m^3/s)
c = volumetric specific heat of air (usually taken as 1200 J/m^3K)
Tim = mean indoor air temperature (°C)
Tom = mean outdoor air temperature (°C)
q = qc + qv = building conductance (W/K)

Indoor building temperature varies around Tim with a $\Delta Tim/2$ value; where ΔTim = Timax - Timin; then, interior temperature (Ti) in any given moment, can be expressed as:

$$Ti = Tom + \frac{Qswm + Qsom + Qim + Qirm + Qevm}{qc + qv} \pm sTi$$ ... eq. 1.4)

where sTi = 'swing' of indoor temperature from the mean: Tim

$\Delta Tim/2$ is often referred to as 'swing' or amplitude (Ti_{ampl}) of indoor temperature.

Accordingly, maximum and minimum temperatures can be expressed as:

$$Ti\,(max) = Tom + \Delta Tm + 1/2\,\Delta Tim \qquad \text{... eq. 1.5)}$$

$$Ti\,(min) = Tom + \Delta Tm - 1/2\,\Delta Tim \qquad \text{... eq. 1.6)}$$

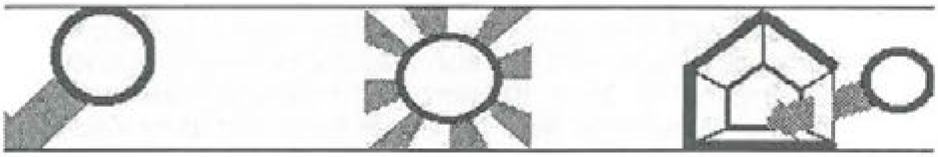
Note that ΔTm is taken between indoor and outdoor temperatures, but ΔTim is the daily variation of indoor temperature.

In warm climates, under normal conditions, the building thermal balance is positive, due to internal and solar gains. The interior temperature is higher than the exterior, then $\Delta T = To - Ti < 0$ (possibly also in daily average terms: $\Delta Tm = Tom - Tim < 0$). Obviously, in warm climate conditions the absolute value of ΔT (or ΔTm) should be reduced, the indoor temperature should not be much higher than the outdoor.

However, depending on the type of climate, it is possible to promote heat losses (Qir, Qev, Qv) and obtain a certain cooling with respect to the exterior environment. Then, an ideal situation where mean indoor temperature is lower than outdoor mean temperature, can be achieved through natural means, that is: $\Delta Tm > 0$. On the other hand, it is also recommended to reduce internal temperature variation (ΔTim), which specifically depends on:

- building thermal inertia (thermal mass)
- outdoor temperature amplitude
- solar energy received and transmitted to the interior and
- the building ventilation regime.

2 REDUCTION OF SOLAR GAINS



Solar radiation can be measured as *irradiance*, G (or intensity, ie. power density) in W/m², or as *irradiation*, H (or incident energy density over a specified period, eg. a day) in Wh/m²day (or MJ/m²day).

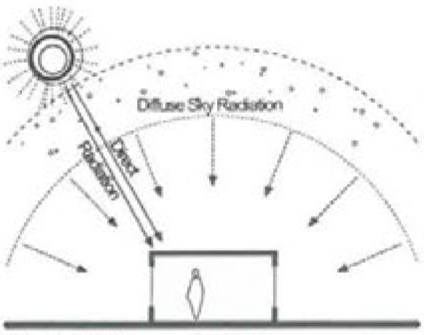


Fig. 2.1 Diffuse and direct components of radiation received by a building

Global short wave radiation, which reaches the earth's surface, is the sum of beam (direct) solar radiation coming from the solid angle of the solar disc, diffuse sky radiation and the reflected radiation from nearby surfaces (Figs. 2.1 and 2.2). The beam irradiance of any surface is the product of the normal beam irradiance, Gbn and the cosine of the angle of incidence, i.

$G = Gb + Gd + Gr$ or $H = Hb + Hd + Hr$ ... eq. 2.1)

$Gb = Gbn \bullet \cos i$ ... eq. 2.2)

$G = Gbn \bullet \cos i + Gd + Gr$ ... eq. 2.3)

where:

G	= global irradiance	H	= global irradiation
Gb	= beam (direct) irradiance	Hb	= beam irradiation
Gd	= diffuse irradiance	Hd	= diffuse irradiation
Gr	= reflected irradiance	Hr	= reflected irradiation
Gbn	= beam irradiance on a plane normal to its direction		
i	= angle of incidence		

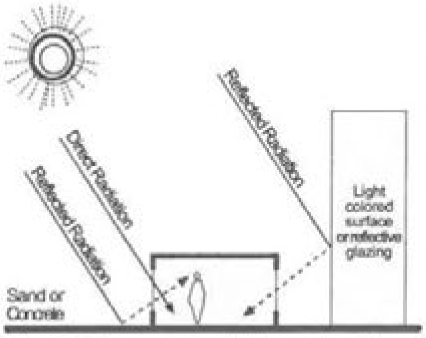


Fig. 2.2 Short wave radiation reflected rom the surrounding area and from neighbouring buildings

The effect of solar radiation on the building constitutes the largest single source of thermal gain, that is why a natural way to reduce heat gain is to control and minimize the solar radiation falling upon its envelope or entering through its transparent elements. The building envelope is the boundary between the variable exterior environment and the controlled interior environment, in which it is desirable to create conditions of comfort suitable for human activities. The building envelope consists of opaque (walls and roofs) and transparent elements (windows), which react differently to solar radiation. Transparent ones will allow solar radiation to enter. Opaque ones will block it, but will absorb part of this radiation. Part of this absorbed heat may be re-emitted towards cooler surfaces or the sky and part of it may be conducted towards the inside of the building.

2.1 Solar radiation on opaque elements

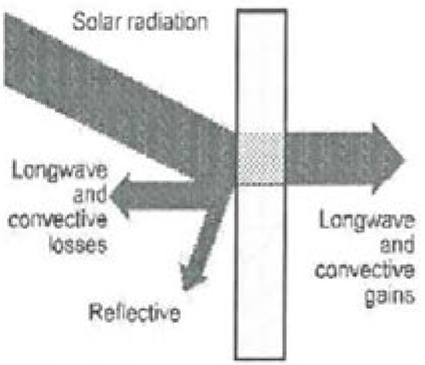


Fig. 2.3 Response of external opaque surfaces to solar radiation

When solar radiation is incident on opaque walls or roof surfaces the following thermal processes will occur:

1) part of the incident solar energy is reflected, that is, returned to the outside in the form of radiation, the rest is absorbed by the surface;
2) the surface temperature increases, exceeding air temperature;
3) part of the energy is dissipated to the exterior by convection and long wave radiation, or transmitted towards the interior by conduction through the element.

Fig. 2.3 shows solar radiation incident on an opaque surface and the resulting heat transfer processes.

Sol-air temperature. For design purposes it is useful to combine the thermal effect of the incident radiation falling upon a building with the effect of air temperature. This can be done by using the concept of *sol-air temperature*. This is the notional temperature which would produce the same heat flow as the incident radiation and air temperature jointly. This notional surface temperature is estimated with the following equation:

$Tsa = To + (G \bullet \alpha - E) / ho$ ... eq. 2.4)
and as $Rso = 1 / ho$ ... eq. 2.5)
$Tsa = To + (G \bullet \alpha - E) \bullet Rso$ ... eq. 2.6)

where
Tsa = sol-air temperature (°C)
To = outdoor air temperature (°C)
α = absorptance
G = global irradiance of the surface (W/m^2)
Rso = outside surface resistance (m^2K/W)
ho = outside surface (heat transfer) coefficient (radiant + convective)
E = long wave radiant emission to sky or cooler surfaces (W/m^2)
[The UK BRE suggests E=20 W/m^2 for an overcast sky and up to 95 W/m^2 for a clear sky for horizontal surfaces. Vertical surfaces face other surfaces at a similar temperature, so E is ignored]

Gertis and Hauser (1975) proposed the use of an adjustment factor (De) in terms of temperature (K) but in this case eq. 2.6 would be different:

$$Tsa = To + G \cdot \alpha \cdot Rso - De$$

where the value of De would be 3 K for vertical and 5 K for horizontal surfaces.

A concept used by some authors in the past is the **solar heat gain factor** (SHGF). It is defined as the fraction of incident solar radiation that is transmitted through an element when air temperature is the same in both sides of the element. In this case heat flow is caused only by the incident solar radiation and not air temperature (Evans 1980). (Not to be confused with the 'Solar Heat Gain Coefficient, SHGC, used for windows, - as discussed on p.24).

$$SHGF = ET / G = U \bullet \alpha \bullet Rso \quad \text{... eq. 2.7)}$$

where:
SHGF = solar heat gain factor
ET = transmitted solar energy = $G \bullet \alpha \bullet Rso \bullet U$ (W/m^2)
G = global solar irradiance (W/m^2)

SHGF is expressed as a decimal fraction (or percentage) and its magnitude depends both on the surface properties and on the U-value of the element. In warm climates any limits set to the magnitude of SHGF are based on a compromise between what is desirable and what is affordable. Koenigsberger et al. (1974) suggested that the SHGF should not exceed 0.04 (or 4%) and Evans (1995) proposed a limit of 0.03 (or 3%), to avoid an increase of the exterior surface temperature of over 4.5 K beyond air temperature (Bansal 1994).

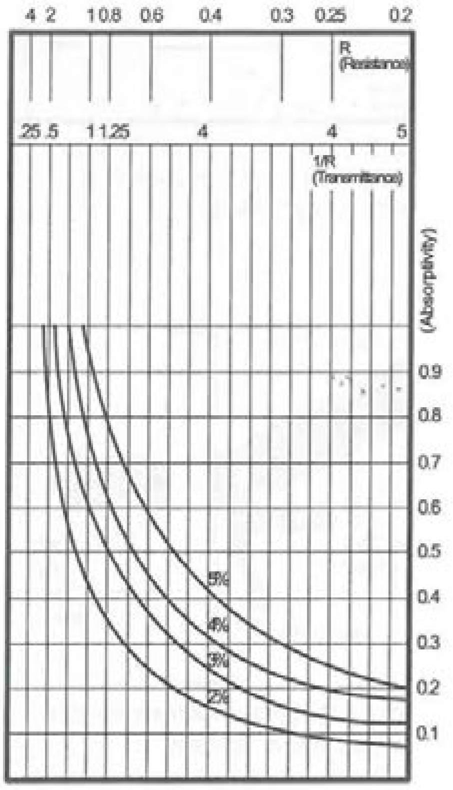


Fig. 2.4 Solar heat gain factor calculator

Table 2.1 shows various constructional elements and their respective SHGF, time-lag and transmittance. Fig. 2.4 shows a graphic calculator which gives the SHGF as a function of absorptance and thermal transmittance (U-value) or air-to-air resistance.

If the building is well ventilated, and the walls are protected from solar radiation (exterior surface temperature = air temperature), thermal insulation will not be necessary, as the temperature difference ΔT will tend to zero and conduction heat flow will also tend to zero. Therefore the SHGF is indicative of the insulation requirement to restrict solar heat gain. In air-conditioned buildings, where outdoor temperatures significantly exceed indoors (ΔT>8K) more insulation will be imperative.

Table 2.1 Solar heat gain factors of various constructions

	construction	U-value W/m^2K	SHGF %	time-lag hours
roofs:				
1	aluminium sheet (new)	8.7	10.2	0.5
2	galvanized iron (GI) sheet (new)	8.5	20	0.5
3	as 2, but rusty	8.5	34	0.5
4	alum.sheet, cavity, fibrous cement ceiling	1.9	4.4	1
5	as 4 + 50 mm fiberglass in cavity	1.3	3	1
6	rusty GI, cavity, fibrous cement ceiling	1.9	7.6	1
7	as 6 + 50 mm fiberglass in cavity	1.3	5.2	1
8	150 mm concrete slab	3.3	9.1	4
9	as 8 + 50 mm woodwool slab internally	1.13	3.1	4.5
10	as 9, but woodwool slab externally	1.13	3.1	13
11	as 8, but both external and internal insulation	0.75	2.1	13.5
12	as 8, but externally whitewashed	3.3	4.1	4
13	as 9, but whitewashed externally	1.13	1.4	4.5
14	as 10, but whitewashed externally	1.13	1.4	13
15	as 11, but whitewashed externally	0.75	0.9	13.5
16	300 mm concrete slab	2.46	6.7	9.2
walls :				
17	250 hollow concr.blocks, rendered both sides	1.7	4.7	11
18	as 17 + external whitewash	1.7	2.1	11
19	230 mm brick wall	2.7	9.5	8
20	as 21 + external whitewash	2.7	3.4	8
21	280 mm brick wall with 50 mm cavity	1.7	6	10.5
22	as 23 + external whitewash	1.7	2.1	10.5
23	corrugated fibrous-cement sheet	8	16	0.5
24	as 25 + 50 mm woodwool slab + cavity	1.2	2.4	0.5

(Evans 1980)

(for windows see Table 2.5: Shading coefficients, p. 24)

2.1.1 Reducing solar radiation impact on opaque elements

Surface-to-volume ratio (S/V) is the ratio of exposed external wall and roof (and any floor with its underside exposed) surfaces to the building volume. A floor on ground or walls in contact with another building, or buried more than one meter deep are not included. Thus, we have:

$$S/V = \frac{\text{exposed exteral surface}}{\text{interior volume}} \qquad \text{... eq.2. 8)}$$

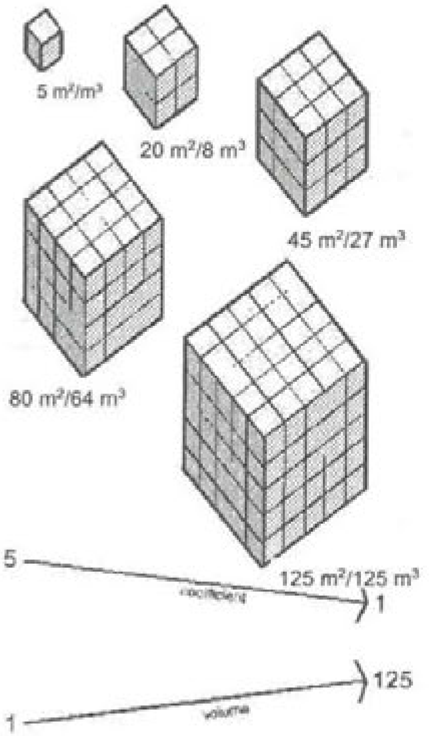


Fig. 2.5 S/V ratio for several cases of cubic shapes

Volumetric heat loss coefficient (GG) is a concept used in some countries, which is the envelope heat loss divided by the volume of the building, or the product of the S/V ratio and the mean transmittance of the envelope: Um. Coefficient GG is an expression of the insulating level of the building envelope, together with its thermal bridges (linear losses). Thus, we have:

$$GG = \frac{S}{V} Um = \frac{q_c}{V} = \frac{\Sigma(AU)}{V} \qquad \text{(in W/m}^3\text{K)} \qquad \text{... eq. 2.9)}$$

(Règles Th-G, 1991). In the assessment of this coefficient, losses due to ventilation should also be considered, but here only aspects relating to the building form will be examined.

When a given form is increased in size, the surface of the walls grows less rapidly than the volume contained. This means that with increasing volume the S/V ratio is reduced (the smaller the building envelope surface is per cubic meter) and therefore, there will be less surface loss. Fig. 2.5 shows the variation of the S/V ratio of a cube when the volume is expanded.

Greater compactness means less surface of contact with outdoor conditions, thus less heat loss or gain. These formal considerations are relevant for hot-dry locations, especially for summer conditions, where, with an exterior envelope area as small as possible, both air-to-air and solar induced heat flows towards the inside of the building are reduced.

For any given constant volume of a building, a fragmented shape, thus an increase of the surface area of the envelope leads to an increase in heat losses and gains. Fig. 2.6 shows the evolution of the S/V ratio of different fragmentations of an 8 m³ volume. Where the S/V ratio is minimized, heat losses or gains will also be reduced.

Different considerations influence the building form in warm-humid locations. Here ventilation (a sensible air velocity) is the most effective mechanism to provide physiological cooling, and reduce the effect of high humidity. A building with an extended arrangement would normally allow more cross-ventilation than a building with a compact design, as it provides more exposed wall area and may make use of the wind from more directions.

Once the building is subject to cross-ventilation during day-time hours, its interior temperature tends to follow the exterior pattern. In this case, the air-to-air heat flow through the envelope is small, and the large surface area does not significantly affect the interior temperature during the day. After sunset and during the night, when the winds usually calm down whilst the air temperature is decreasing, the larger area of the envelope allows faster cooling.

If the internal habitable space is air-conditioned and the external surface is exposed to solar radiation, the volumetric response should be compact, as this would minimize the heat gains

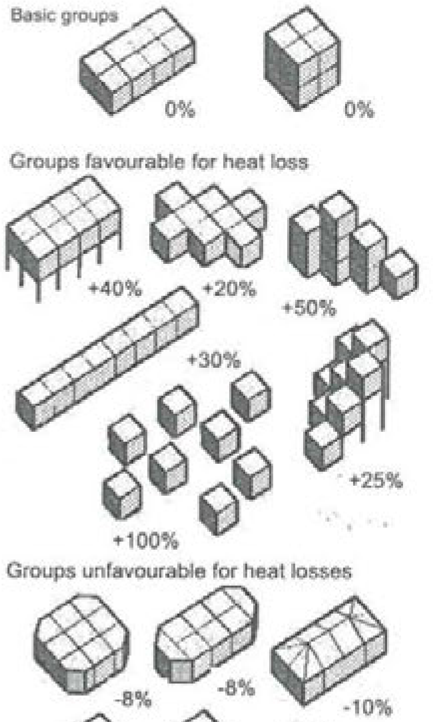


Fig.2.6 The effect of massing on heat losses and air-to-air gains

In rooms ventilated with passive cooling systems, the volumetric response will depend on the requirements of the adopted system. For systems that rely on storage of heat during the day and its dissipation overnight, a compact design would be more effective; but those based on natural convective principles may work better with a fragmented type of design.

When the exterior surface is exposed to solar radiation, the surface temperature increases considerably, which causes an increased heat flow towards the interior of the building.

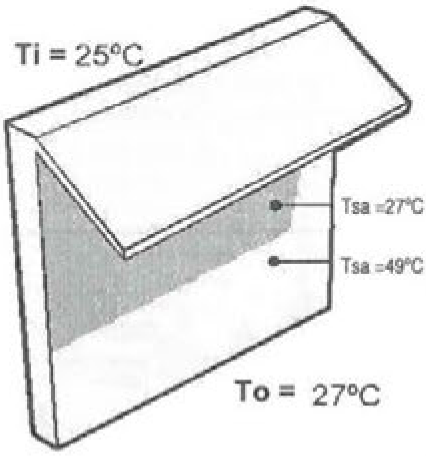


Fig. 2.7 Solar protection for external walls

Shading is the use of opaque devices between the sun and the envelope elements which significantly reduces the incoming heat flow. If the beam irradiance is thus eliminated and the diffuse irradiance is reduced, the global irradiance (G) tends to zero, then the heat absorbed, ($G \bullet \alpha \bullet Rso$) will also tend to zero, and the external surface temperature will be close to the temperature of the air. The heat flow to the interior of the building (Q), will then be smaller than that of an unshaded envelope element.

The conductive heat flow through an opaque element receiving solar radiation on its external face can be expressed as follows:

$$Q = U \bullet A \bullet (Tsa - Ti) \qquad \text{... eq. 2.10)}$$

where:
- Q = conductive heat flow (W)
- U = thermal transmittance (W/m^2K)
- A = area of the element (m^2)
- Ti = interior temperature
- Tsa = sol-air temperature, as per eq. 2.6

For example:

two wall elements of a given enclosure have similar orientations and dimensions, but one is exposed to solar radiation whilst the other is shaded by a horizontal device. Determine the thermal conditions and the heat flow through each of the two elements.

a) Data:

beam irradiance:	Gb	= 600 W/m^2
diffuse irradiance:	Gd	= 90 W/m^2
reflected irradiance:	Gr	= 35 W/m^2

- U = 1.2 W/m^2K
- To = 27 °C
- Ti = 26 °C
- α = 0.5
- Rso = 0.08
- A = 18 m^2

b) Calculation:

shaded :

(Gb is eliminated and assume that Gd is reduced to half)

$Tsa = To + G \bullet \alpha \bullet Rso = 27 + (45+35) \bullet 0.5 \bullet 0.08$

$Tsa = 30.2°C$

$Q = U \bullet (Tsa - Ti) \bullet A = 1.2 \bullet 30.2 \bullet 18 = 90.7\ W$

sunlit

$$Tsa = 27 + 725 \bullet 0.5 \bullet 0.08 = 56°C$$

$$Q = 1.2 \bullet (56\text{-}26) \bullet 18 = 648\ W$$

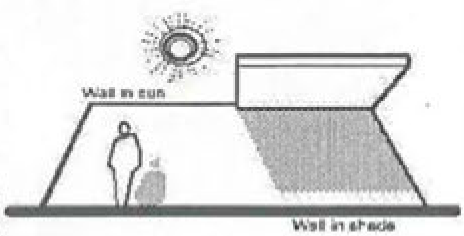


Fig. 2.8 Wall, with different conditions of solar exposure

This example shows that whilst the temperature difference between the indoor and the outdoor in the shade is 4.2 K, in the sunlit case the difference is 30 K. Although the shaded wall receives some diffuse and the reflected radiation, the heat flow through the wall exposed to solar radiation is some 7 times larger.

Shading devices can be **horizontal** , such as eaves, horizontal louvres, an awning, or **vertical**, such as fins or vertical louvres

A) Horizontal devices

If roofs and walls are shaded with panels separated from the building by a gap to allow external air circulation, immediate solar thermal load penetration is blocked. Energy flux contributions through solar protection are described as follows:

1) The external face of the sunshade absorbs part of the solar radiation and the rest is reflected;

2) The absorbed flow partly dissipates to the outside by convection and long wave radiation. Another part dissipates by conduction towards the other face of the sunshade.

3) The heat flow passing through the sunshade partly dissipates in the air behind the sunshade by convection, and is partly transmitted towards the external face of the wall or roof by long wave radiation;

4) Part of the flux absorbed by the external face of the wall or roof dissipates in the air by convection. Another part is conducted to the internal face of the element (see Fig. 2.9)

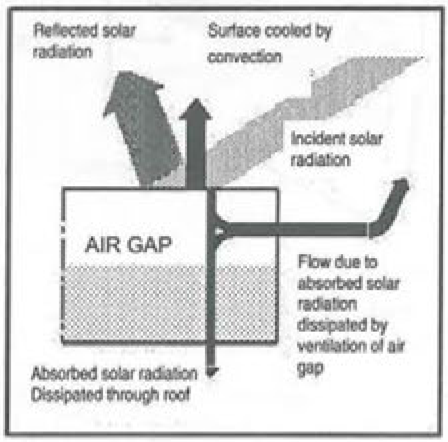


Fig. 2.9 Solar radiation and heat transfer mechanisms in a horizontal (parallel) shading device to an external opaque surface

A solar protection for a roof (a 'parasol roof') made of pre-fabricated panels (concrete, galvanized iron sheets, or fibrous cement) provides control of direct beam radiation, but does not allow radiation to escape towards the night sky (Fig. 2.10). The solar protection should be light and movable (pivoting, extendable, sliding, etc.), to allow manual or automatic adjustment, so as not to interfere with night radiant cooling of the roof surface (see Fig. 2.11).

An alternative is covering the roof with vines. Evaporation from the surface of the leaves will make their temperature lower than the air temperature. Even at night time, their temperature may be lower than the air by radiation to the much lower sky temperature (Fig. 2.12).

B) Vertical devices

A solar protection system consisting of vertical fins attached to an opaque building surface is based on heat dispersion principles by cooling fins. It is the same as that used for some air-cooled engines

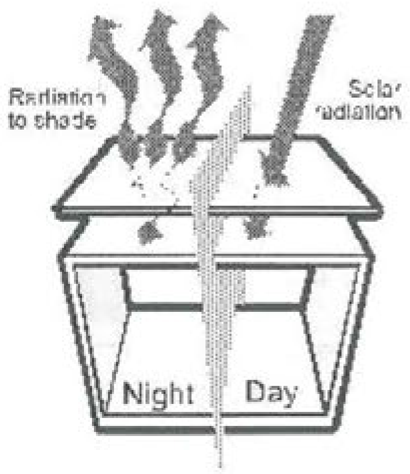


Fig. 2.10 Shading of a roof by a fixed system of parallel shade

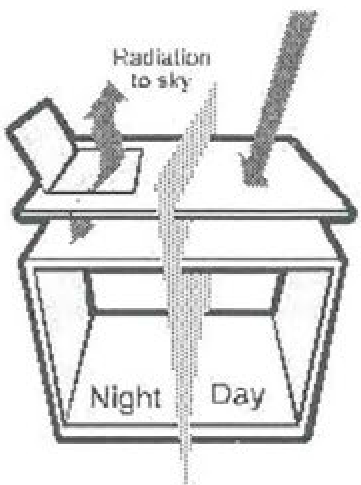


Fig. 2.11 Roof shading by a movable parallel shade

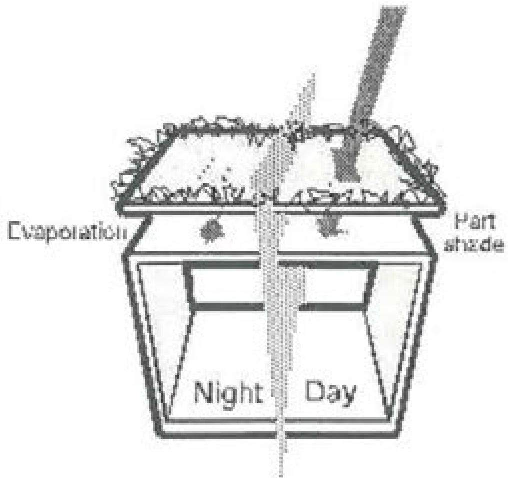
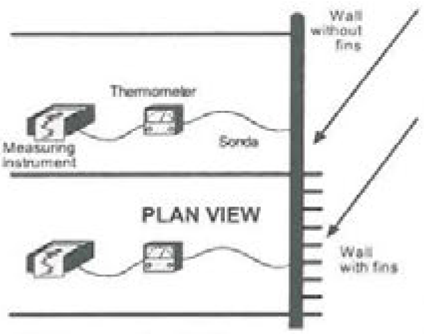


Fig. 2.12 Cover protected by vegetation elements that provide shading and evaporative cooling



Simultaneous registration of temperature changes at two levels of the wall façade with and without cooling fins

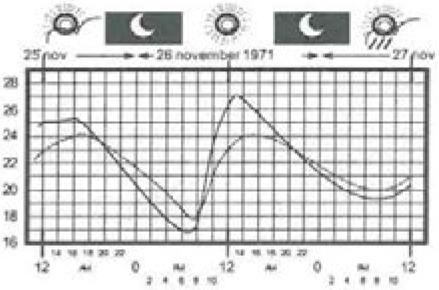


Fig.2.13 A specific example: temperatures of a wall with— (dotted line) and without fixed perpendicular fins (solid line)

(for example: aviation and motorcycle engines). The use of this shading strategy promotes heat exchange by convection, by pressure differences generated in the surface of the envelope, due to small temperature variations. These are particularly effective under windy conditions.

The addition of such rigid fins to the building will reduce heating of the walls and will provide shade. It will also lessen heat flows towards the interior, because the fins will provide more contact with the air. Fig. 2.13 shows this type of solar protection, as well as interior temperature readings for east walls, with and without fins.

C) Building massing

The building mass (form) can be shaped so that it provides a certain degree of self-shading. If the building is designed with a staggered configuration, (either in plan or in section) some mass elements may cast a shadow on the surfaces of other elements (Fig. 2.14).

D) Surface conductance

'Roughness' is an expression of the surface texture of building elements indicating small scale unevenness. Grades of roughness are established according to the size of the grain, expressed in millimetres. This grade of roughness has little effect on temperature. However, a very rough surface enhances radiative exchanges, especially with the sky as well as surface to air convective exchanges. If the rough texture of the facades is altered to decrease surface resistance (Rso), then the external surface sol-air temperature will also decrease.

Highly textured walls have a part of their surface shaded. The radiation absorption area of such a textured surface is smaller than its radiation emission area (to sky and other surfaces of the surroundings), and will thus be cooler than a flat surface. The enlarged area also means an increase in the convective heat transfer, which will allow faster cooling of the building during night time, when the surrounding temperature is lower than the temperature of the building.

Fig. 2.15 shows such shading by texture.

There are many ways to create rough textures, from a rustic finish of the walls to the choice of appropriate sheathings.

E) Radiative properties

All materials absorb part of the incident solar energy and re-emit some of the absorbed heat.

Absorptance (α) is a surface quality, indicating the ability of the surface to absorb the radiation it receives and it is expressed by a decimal fraction.

Emittance (ε) is a measure of the ability of a surface to radiate (emit) heat or other electromagnetic radiation.

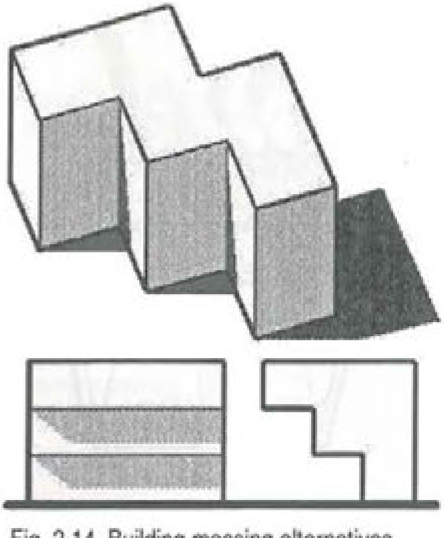


Fig. 2.14 Building massing alternatives in elevation and section (cantilevered upper floors) in order to generate self shading

The sum of absorptance (α) and reflectance (ρ), is always the unity: $\alpha + \rho = 1$. If a surface has an absorptance of 0.30 (30% of incident radiation) its reflectance is 0.70 or (70% of the incident radiation). For the same wavelength (temperature) of radiation $\alpha = \varepsilon$, but many surfaces are 'selective', ie their α and ε properties vary with the wavelength of radiation. The sun, as a high temperature (≈ 6000°K) body, emits short-wave radiation, especially in the visible spectrum and short infrared, whilst building surfaces at terrestrial temperatures (<100°C), emit invisible long wave radiation.

If absorptance decreases, then the product G • α • Rso also tends to zero, and surface exterior temperature will be close to that of the air, and the heat flow to the interior of the building, Q, will be smaller.

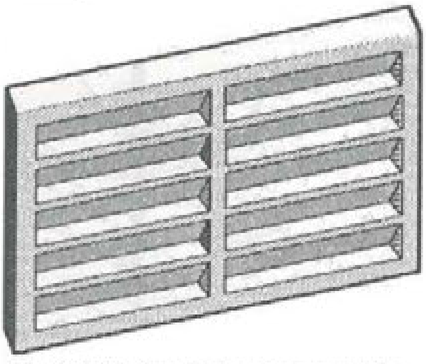


Fig. 2.15 Texture to increase convective exchange+ provide small scale shading

The external surface colour has a significant effect on the impact of the sun upon the building and the temperature in the interior spaces. Materials with darker colours, such as black, are the most absorptive, whereas light colours are the least absorptive. Table 2.2 shows absorptances of colours, ranging from lighter to darker. Fig. 2.16 a and b each shows five temperature curves: external surface, air DBT and inside surface temperatures of three different thicknesses of Ytong (autoclaved aerated concrete), a: with outside surface grey, b: with outside surface white.

There are selective surfaces that absorb only a small part of solar radiation, but emit radiation freely. They maintain relatively low temperatures even when exposed to the sun. White paint is a good example, which may have a solar absorptance of only 0.2 - 0.3 but an emittance at temperatures <50°C of 0.8 - 0.9. There are also other materials that absorb a high proportion of solar radiation, but have reduced emittance. These surfaces maintain high temperatures and reduced heat losses, used to advantage in solar collectors

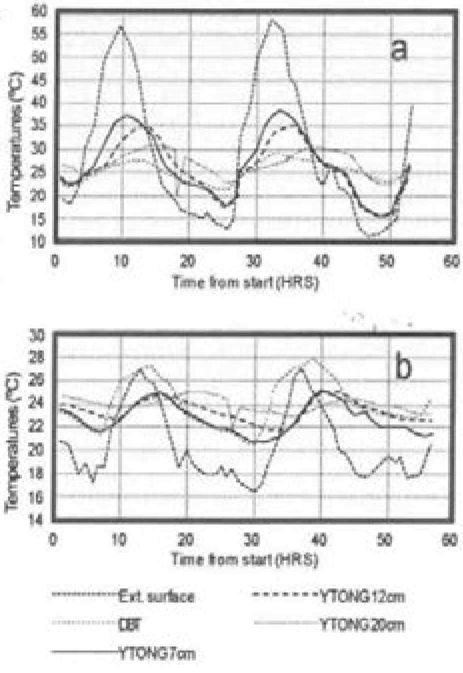


Fig. 2.16. Temperatures obtained in covers from several thicknesses of Ytong painted

Table 2.2 Absorptances of dark and light colours

category: absorptance	light <0.5	medium 0.5 - 0.7	dark 0.7 - 0.9	black >0.9
colours	white beige	dark red light green orange light red	brown dark green light blue	black dark brown bright blue dark blue

(Evans, 1995)

Table 2.3 Building surfaces: solar α and low temperature ε

material	emittance ε at 20°C	solar absorptance α
solid red brick	0.93	0.54
roof tiles, terracotta, brown	0.94	0.76
limestone, sandstone	0.96	0.60
concrete, (plain, off-form)	0.96	0.55
plastering, white	0.97	0.36
plastering, gray	0.97	0.65
anodised aluminium	0.90	0.20-0.40
polished aluminium	0.02 - 0.04	0.10–0.40
window glass	0.90	0.04–0.40 (depending on τ)

(Izard, 1993)

2.2 Solar radiation on transparent elements

Windows have several functions in any climate; they provide natural light, visual contact with the outside, sun penetration in winter, and ventilation in summer. We will treat the impact of window design in the behaviour of the building regarding solar radiation.

Transparent materials such as glass, and certain types of plastic have the property of transmitting radiant energy with only small losses, especially the radiation of the visible band, but are opaque to long-wave (infrared) radiation. Once the radiation has penetrated and is absorbed by internal surfaces, it is re-emitted with longer wavelengths (corresponding to the temperature of these surfaces), which, in the most part, cannot penetrate the glazing (greenhouse effect). Fig. 2.17 shows how incident radiation is partly reflected, partly absorbed and then transmitted in a single glazed transparent element.

As stated earlier, for opaque surfaces absorptance + reflectance = 1
$\alpha + \rho = 1$

transparent surfaces: absorptance+reflectance+transmittance = 1
$\alpha + \rho + \tau = 1$

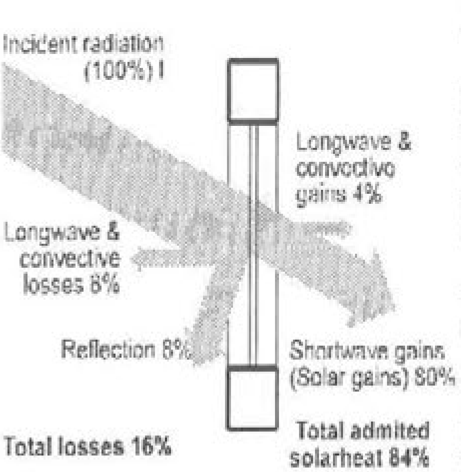


Fig. 2.17 Solar energy balance for a single glazed window

However, part of the absorbed component will be re-emitted, thus the total **solar gain factor** will be transmittance + some part of absorptance, often taken as half (although this fraction depends on the ratio of air and radiant temperatures on the inside and outside)
$\theta = \tau + 0.5 \bullet \alpha$

Thus while τ (tau) is an optical factor, θ (theta) includes the re-emitted heat. ($\theta \neq$ SHGF, or solar gain factor, discussed on p. 12).

There is considerable confusion in the literature about the solar gain factor. Some authors restrict its use for the glass only, excluding the frame or any shading device, others use it as an average value for the overall window area, perhaps including shading devices. Some measure it at normal incidence of solar radiation, others use it as an instantaneous value, as a function of the angle of incidence. In some sources it is the daily average value for a window/shading device combination. If any data are to be used, the user should check its meaning or derivation.

The following equation is used to determine the solar radiation heat gain through a glazed opening: solar radiation intensity (G) is multiplied by the area of the opening, and by the solar gain factor (θ) which depends on the quality of the glass and angle of incidence (measured from the normal to the surface). Thus the heat flow equation is:

$Q = A \bullet G \bullet \theta$ ... eq. 2.11)

where

A = window area (m^2)

G = global irradiance (W/m^2) on the window surface

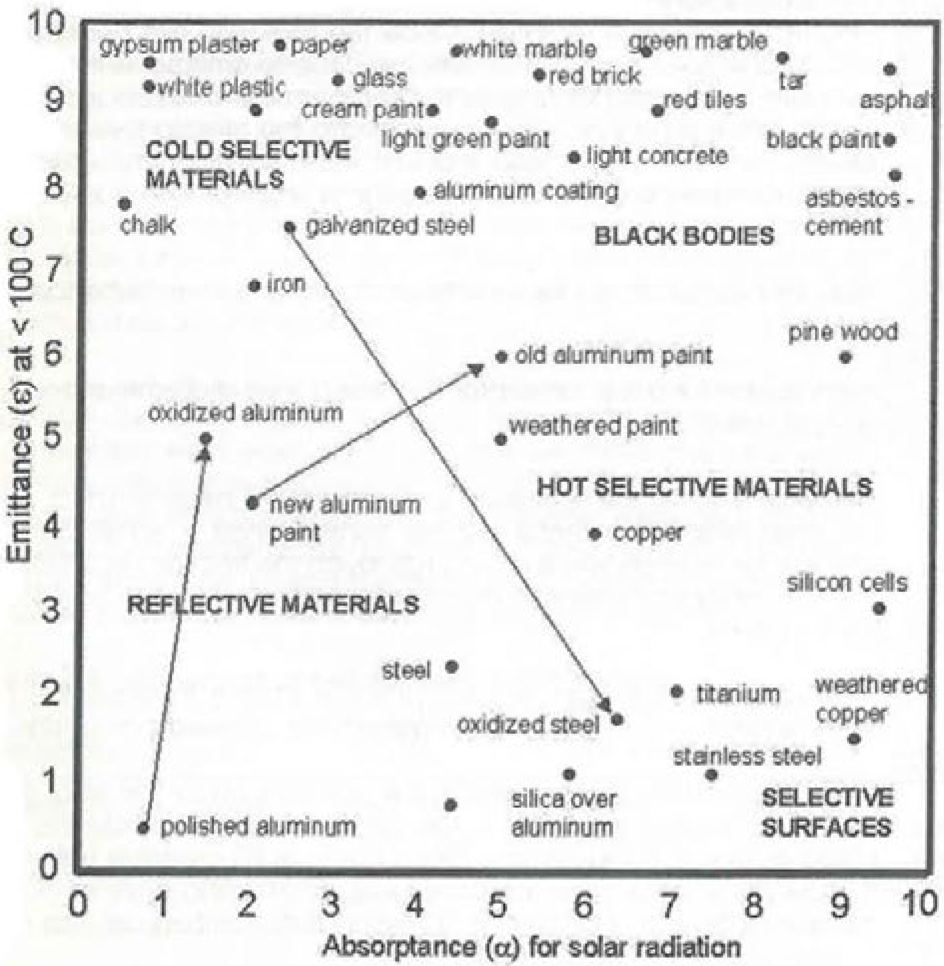
θ = window glass solar gain factor

or in case of an unglazed opening

$Q = A \bullet G$ ... eq. 2.12)

(Koenigsberger et al, 1977)

Table 2.4 Absorptance vs emittance of various surfaces



2.2.1 Reducing solar radiation impact on transparent elements

The **orientation** of buildings and glazed surfaces has an important influence on the energy contributions to habitable spaces. The determinants are: maximum irradiance received, time of day when this maximum irradiance occurs, duration of solar exposure of the surface and foreground reflectance (albedo). Fig. 2.18 shows solar radiation effects in different northern latitudes and orientations.

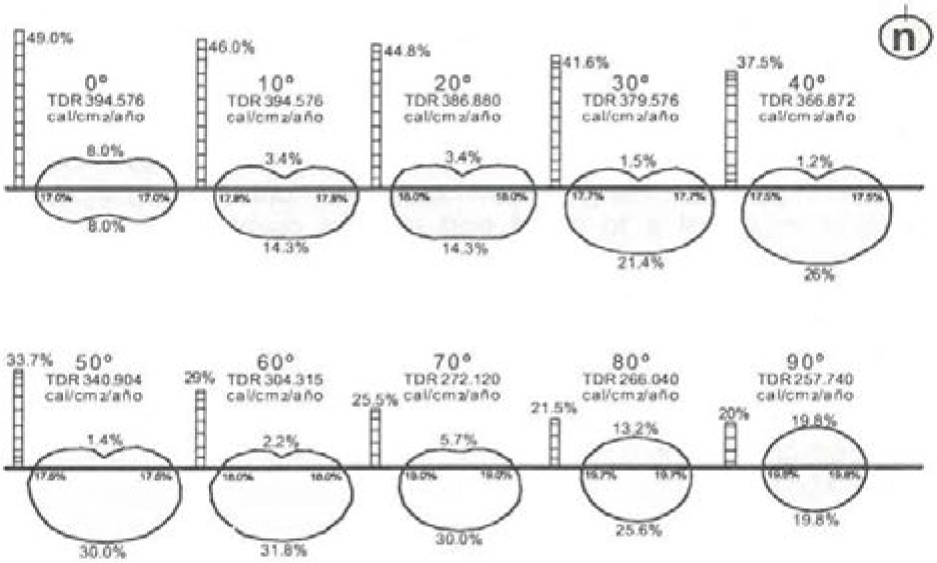


Fig. 2.18 Solar radiation effects at various north latitudes (Olgyay, 1968)

The 10 polar diagrams (from the equator to the north pole) illustrate the comparative magnitude of direct (beam) solar irradiation over a year on vertical surfaces of all orientations. If the total received by the four surfaces of cardinal orientation plus the roof is taken as 100%, (the TDR or "total direct radiation"), the percentage numbers indicate the magnitude received by each surface; eg. for 0° latitude the four walls receive 8 + 8 + 17 + 17% = 50% plus the roof (indicated by the bar) 49%

Many authors discussing bioclimatic design consider that the most favourable orientation for a facade in high and medium latitudes is the one that faces the equator (south in the northern hemisphere and north in the southern hemisphere), because this orientation is the only one that receives solar radiation for a shorter period in summer than in winter and with a larger incidence angle; and in winter receives the maximum hours of sunshine, with a smaller incidence angle. East and west facades receive more exposure to the sun in summer than in winter. Facades with a polar orientation (north in the northern hemisphere and south in the southern hemisphere) do not receive sunshine in winter, and would receive the maximum of sunshine hours in summer. Fig. 2.19 shows control and use of solar radiation in a south facade (northern hemisphere) in winter and summer.

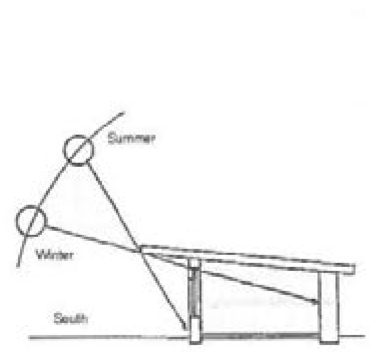


Fig. 2.19. Equatorial orientation gives an automatic control of the solar radiation (medium and high latitudes)

Fig. 2.20 shows the mean coefficient of variation of solar contributions in Angers, France (47°28'N) for different orientations relative to the south façade: (a) for summer (May - September) and (b) for the heating season (October - April). In the summer east and west orientations receive as much energy as the south facade, and southeast and southwest orientations have an even greater irradiation. During the heating period, the south façade is more favoured; east and west facades receive less than half of the irradiation of the south. Southeast, south, and southwest orientations are to be favoured.

It is recommended that the building should be oriented with its longer walls facing north and south, so that only the shorter walls are exposed to the east and west, where the sun is more intense during the morning and the afternoon.

In inter-tropical latitudes, where seasons are barely differentiated and where the sun path is near the zenith (and seasonally moves both north and south) choosing between south and north is not significant. What is important is to avoid east or west orientations that are exposed to the sun's rays in the morning and in the afternoon with incidence near to the normal of the facades and which are thus more difficult to protect. If the glazed-in surface is turned about a vertical axis, away from the direction to the sun (resulting in a sawtooth plan form), or tilted forward in section, to obtain incidence angles larger than 50° during critical hours, thermal gain is significantly reduced and can, in a some cases, avoid external shading devices. (Fig. 2.27)

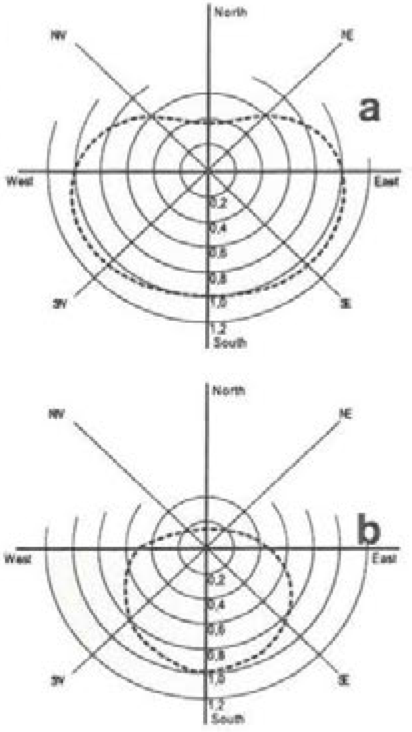


Fig. 2.20 Coefficient of variation of solar contributions for Angers as a function of orientation (Cardonnel, 1983)

Orientation for the prevailing wind can be the determinant factor in some situations, as for example in the coastal tropics, or in locations with a high relative humidity, or where frequent and intense winds are to be avoided. In most cases solar orientation is fundamental and is more important from the thermal, climatic, hygienic and psychological point of view. Solar orientation is even more important as we move away from the coast.

The size of glazed surfaces is the primary determinant of the amount of total solar energy (diffuse, direct, global) that would penetrate the building.

An increase in the glazed surface of an inhabited space always results in an increase of the interior air temperature, especially during day time, which in turn leads to an increased amplitude of the interior temperature variation.

Glazing ratio (gr), which is sometimes referred to as 'transparency coefficient' (T) is the ratio of glazed surface and the overall wall surface of the building. Thus we have:

$$gr = T = Sg / St \quad \text{... eq. 2.16)}$$

where:
- gr = glazing ratio
- Sg = glazed surface
- St = total wall surface

This can be applied to an element or to the whole building.

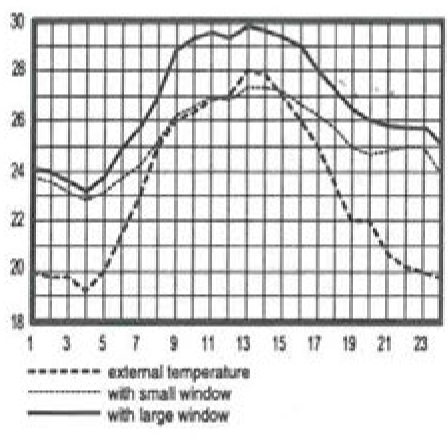


Fig. 2.21 Temperature profile with large and small windows (Izard, 1993)

According to bioclimatic requirements of the location the desirable glazing ratio will tend to be lower in inter-tropical regions and larger in mid- or high latitudes.

Fig. 2.21 shows hourly variation of interior temperature of a given building with small and large windows. Towards noon, the difference between small and large windows exceeds three degrees.

Shading devices can be used to control solar input. The largest heat gain in a building is caused by solar radiation penetrating through windows. The use of opaque devices between the sun and the window will limit the penetration of solar radiation into the building.

In a comparative study of the heat flows (both conduction and radiation) through a timber framed wall painted a light colour (U=0.74 W/m²K) and a single glass pane, both facing west, over a cloudless average summer day in Miami, it was demonstrated that the glass is 30 times more vulnerable to the sun than the wall (Fig. 2.22). When shading the glass, the effect in terms of daily total is reduced to one third. Such comparisons are affected by several conditions, such as the latitude, orientation, time of the year, etc. (Olgyay, 1963).

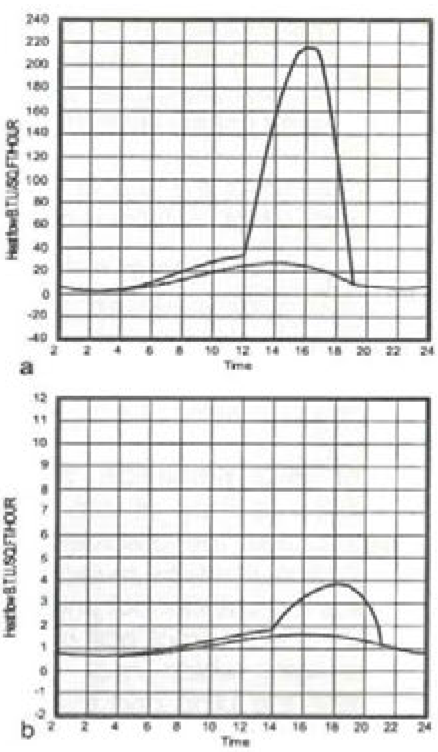


Fig. 2.22. Heat transmission in (a) a glass pane, (b) a wooden wall (Olgyay, 1963). In both cases the lower curve is the heat gain when shaded.

The effectiveness of exterior solar protection is at its maximum if the intercepted solar radiation is reflected, because the heating effect on the surface of the shading device itself is reduced.

Solar protection systems or shading devices are classified as fixed or adjustable (Fig. 2.23). Fixed devices are rigidly attached to the building without any facility for adjustment, so their action is constant. Movable sunshades allow the possibility for adjustment or regulation, their parts can be adjusted manually or automatically, but these require more maintenance.

Fig. 2.24 presents the results of a series of thermal models (which are not ventilated); those in the first series are without shading devices and those in the second have external solar protection (venetian blinds), for a series of orientations. The results of the second series show that the difference of interior temperature for the different orientations (north, south, east and west) is quite small and the temperature for all orientations narrowly follows the same pattern. In the case of the most unfavourable direction (the west), the 16:00 hour temperature maximum value of the first series is reduced by about 9 degrees due to the presence of the shading device (Givoni, 1994).

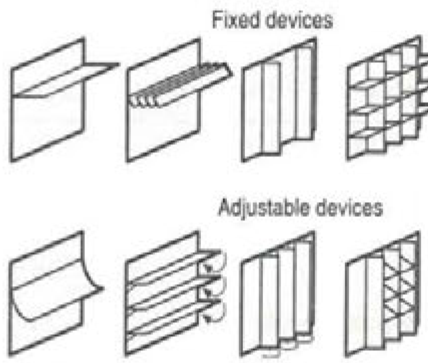


Fig. 2.23. Adjustable and fixed devices. Examples of external solar protection.

The **shading coefficient** (SC) has been used as a measure of the effectiveness of the shading device, which is a decimal fraction, the ratio of the quantity of heat gained (by absorption, transmission and radiation) by the shaded glass to the heat gained by an unprotected clear glass in a typical window.

$$SC = \frac{\text{solar heat gain of given fenestration}}{\text{solar heat gain of reference glass}}$$

the reference glass has the following properties at normal incidence:

$a = 0.06$; $r = 0.08$; $t = 0.86$

Clear glass would have a shading coefficient of 1, and the value 0 would indicate a total blocking of all solar radiation. Sometimes SC was used for a glass/shading device combination measured at normal incidence, sometimes as an instantaneous value for a given incidence, sometimes average value for a given location, time of the year and orientation. Table 2.5 gives the shading coefficients for different types of solar control elements.

In recent times the use of the solar heat gain coefficient (SHGC) is favoured, which is defined as

$$SHGC = \frac{\text{solar heat gain of given fenestration}}{\text{solar irradiance on the outer surface}}$$

The term 'fenestration' in both cases means the window, together with any shading devices and in case of the SHGC it accounts for the average properties of window glass and frame.

Interior solar protection, blinds and inside curtains are not very effective, as they absorb solar heat and can reach quite high temperatures. The absorbed heat will warm the inside air, partly by convection, partly by re-radiation. Half of this re-radiation takes place towards the outside, but since it is long wave, the glass of the window blocks it. Only a small part may be reflected by the blind at its original wavelength, which may escape through the glass. The space between the blind and the window is overheated, the heat is then distributed to the room by convection and the heat of the blind itself makes the mean radiant interior temperature go up above the air temperature (Fig. 2.25).

Reflection by the glass itself can also block solar radiation. Fig. 2.26 shows that transmittance is almost constant for an angle of incidence between 0° and 45°. Beyond 70° there is significant reduction in transmittance for the solar radiation by a strong increase in surface reflection. This optical property of glass can be applied in the window geometry: a forward sloping glass surface will create large a angle of incidence thus it is practically opaque for solar radiation. (Fig. 2.27)

Table 2.5 Shading coefficients (SC) of some window systems

window system		shading coefficient
Glazing	clear glass, 3 mm	1.00
	clear glass, 12 mm	0.90
	heat absorbing or tinted	0.50—0.80
	reflective	0.20—0.60
Internal devices	venetian blinds	0.45—0.65
	roller shades	0.25—0.60
	curtains	0.40—0.80
External devices	eggcrate	0.10—0.30
	horizontal overhang	0.10—0.60
	vertical fins or louvres	0.10—0.60
	trees	0.20—0.60

Absorptance (α) is an optical property of glass that is open to modification, through the use of additives which tint the body of the glass. Although the tinted glass reduces light transmission, it does not usually reduce thermal gain to the same extent, since the absorbed radiation heats the body of the glass, which is then re-radiated to the inside. A type of tinted glass is called *heat absorbent* as it has selective properties: it absorbs part of the short-wave infrared

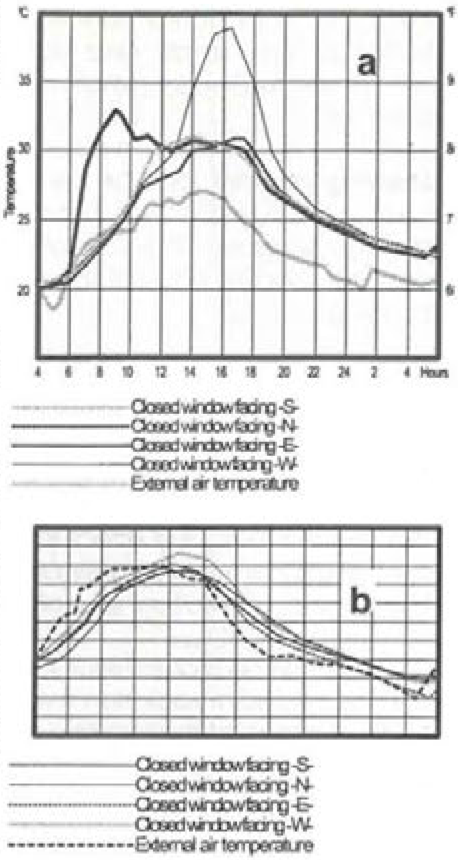


Fig. 2.24 Internal temperatures registered in thermal models (a) without and (b) with shading devices (Givoni, 1994)

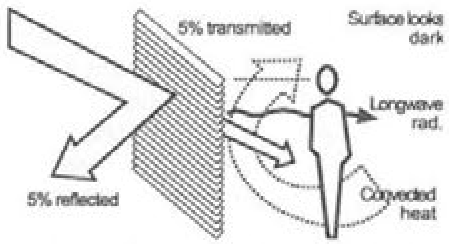


Fig. 2.25 Thermal behavior of a shade of dark colour

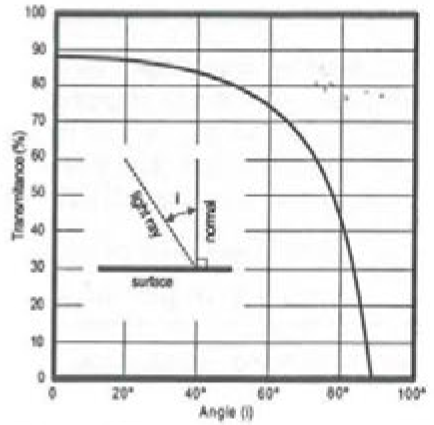


Fig. 2.26 Solar radiation transmittance through a glass surface as a function of angle of incidence

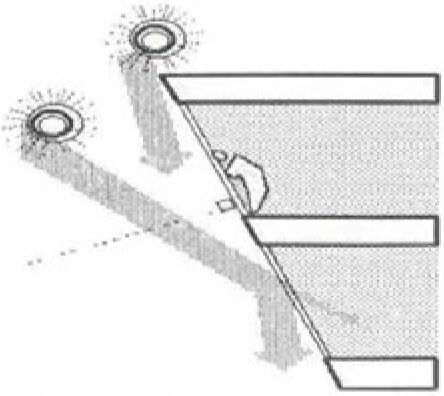


Fig. 2.27 Reflection of the greater part of the solar beam by a tilted glass surface due to the large angle of incidence

radiation much more than the visible part. It will slightly reduce solar heat gain, but it gets heated and the problem of re-radiation still occurs. The behaviour of a heat absorbent glass exposed to solar radiation in is illustrated in Fig. 2.28.

Selective transmittance (τ) means that the transmittance varies with the wavelength. When natural light is desired, but not solar heat, it would be a great advantage if the visible component of the solar radiation could penetrate, at the same time that the infrared solar radiation was blocked. Certain *selective* glass systems (low-e) can do this to a limited extent.

Fig. 2.30 shows that low-e glass transmits 'colder' light than other glazing materials, because these transmit a bigger proportion of the visible radiation than of the infrared. This type of glass is also useful in winter, because it allows less loss of radiant heat than a conventional glass.

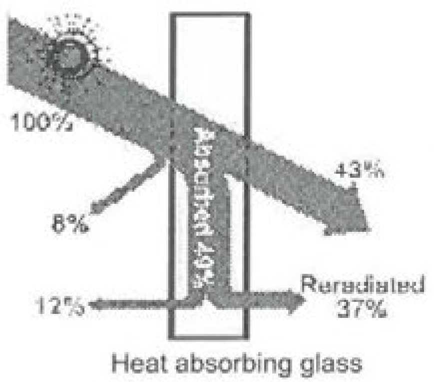


Fig. 2.28 Energy balance in a window with absorbent glass

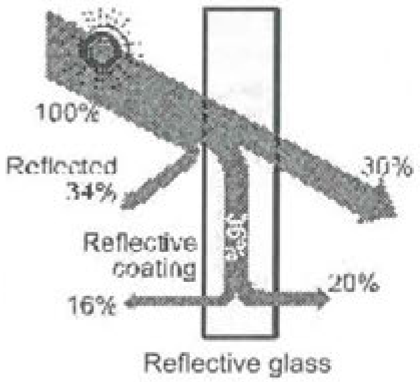


Fig. 2.29 Energy balance in a window with reflective glass

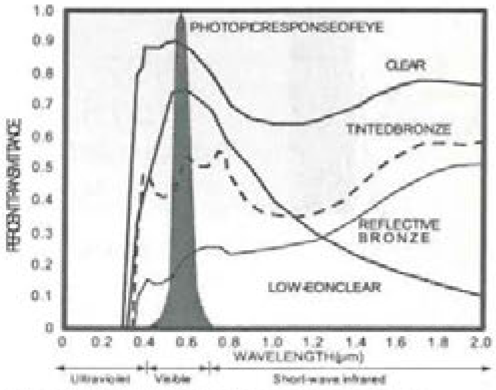


Fig. 2.30 Solar transmittance in a selective glass the (low-e) as a function of wavelength

Reflectance (ρ) for solar radiation of the window glass can be significantly increased by the addition of a metallic reflective coat to the glass surface. This reflectance can be selective, its properties depend on the thickness of this coat, it can block the infrared part of solar radiation whilst admit much of the visible part of the spectrum. However, in winter this treatment reduces the utilization of solar energy in a passive system. Reflective glass is appropriate for east and west facades. Such selectivity can be engineered to suit the task; for example a low-e (low emittance) coating on the inside face of a pane can be used to reduce heat losses in a cold climate, whilst in warm climates it can be used to reduce heat gain.

Photochromic glasses of several types have recently been developed. Most include crystalline submicroscopic particles which turn dark when exposed to intense light, and they recover their transparency when the illuminance is reduced. Its transmittance may vary between 0.74 (when clear) and 0.01 (when darkened).

Insulating glasses have a much reduced thermal transmittance. Whilst the U-value of ordinary single glazing is around 6 W/m^2K, insulating windows with U-values below 1.5 W/m^2K can be constructed in several ways. Most common are the sealed double and triple glazed systems using low-e coatings and noble gas filling of the cavity between the transparent layers. In window systems using double glazing units with low-e coating and argon, U-values about 1.3 W/m²K can be obtained and with evacuated low-e coated double glazing units, about 0.56 W/m²K has been obtained.

There is a new type of material, still in the experimental phase, the silica aerogel, transparent to visible radiation (light) and highly insulating. Its thermal conductivity is around 0.021 W/m.K; lower than that of still air (0.026 W/m.K). In an evacuated aerogel glazing constructed as a sandwich by inserting a 20 mm thick aerogel layer between two glass panes U values around 0.5 W/m²K were reached (Duer and Svendsen, 1998). In air-conditioned rooms, this type of glass, because of its thermal resistance, is perfect for the control of loads. However, it should be avoided in non-conditioned buildings
(Fig. 2.31).

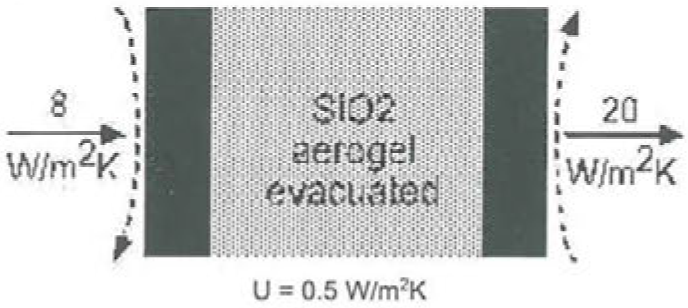
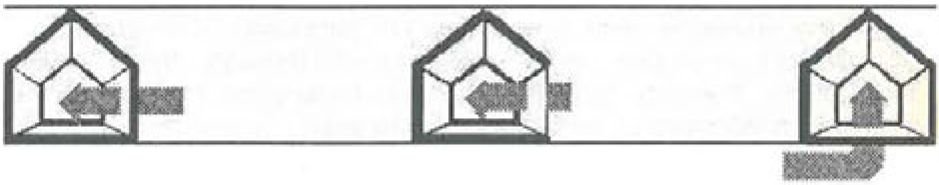


Fig. 2.31. Section of an improved glazing system (evacuated to p < 5 kPa)

Such glasses are very useful in cold winter climates, where there is a large outdoor—indoor temperature difference, where heat loss should be reduced to a minimum, but solar heat gain is very desirable, but certainly not in warm climates.

3 REDUCE CONDUCTION THROUGH THE ENVELOPE



3.1 Heat conduction

Heat is a form of energy appearing as molecular movement in materials or as electromagnetic radiation in space. In a solid body, or bodies in contact, heat flow by conduction takes place directly between adjacent particles of the material when molecules transfer heat (molecular motion) from hotter to cooler points.

The rate of heat flow varies from one material to another and it is defined by Fourier's equation. Eq. 3.1 is derived from the Fourier equation and indicates that the heat flow rate depends on the thermal conductivity of the material, its thickness (length of heat flow path), the cross sectional area available for conduction, and the temperature difference between the two points considered:

$Q = (\lambda / b) \bullet A \bullet \Delta T$ ... eq. 3.1)

where:

Q = heat flow rate or heat flux (W)

λ = thermal conductivity of the material (W/m.K), a characteristic the material that indicates its capacity to transmit the heat flow. It is the heat flow rate per unit of surface, with a unit of temperature difference, between two points at a separation distance of one unit. A material with a high conductivity value will allow a higher flow of energy

b = breadth or thickness of the element, it expresses the length of heat flow path (m).

A = element surface or area through which heat is transmitted; taken perpendicular to the heat flow (m^2)

ΔT = temperature difference between the two faces of the body. In the case of a building envelope it is the difference between the external and internal faces.

Equation 3.1. shows that the heat conducted through any material is proportional to the area perpendicular to the heat flow, to the conductivity of the material, and to the difference in temperature between its two faces, and it is inversely proportional to the thickness of the material.

3.1.1 Conductivity and conductance

The term λ/b (W/m²K) is referred to as conductance. Conductivity is a material property independent of its shape or size, whereas conductance (C) is a property of a body of given thickness. Resistance (R) is the reciprocal of conductance, a much more commonly used value, expressed in m²K/W.

$R = b / \lambda$ ... eq. 3.2)

The quantity 'conductance' is rarely used in practice (except as surface conductance). However, the term 'conductance' is often used with a different meaning, as introduced on p.9: qc, qv and q, all measured in units of W/K.

When the envelope (wall, floor or roof) is composed of several layers of different materials, heat must travel through these layers sequentially; therefore the heat flow will depend on the sum of the individual resistances of the component layers.

R_{body} = R1 + R2 + ... Rn ... eq. 3.3)

where:

R_{body} = total resistance of the body

R1... Rn = resistance of each of the layers

When the external surface is exposed to solar radiation, the surface temperature of the external face of the opaque element can increase considerably; therefore, heat flow to the interior or the building will also increase. The temperature difference will be taken between the sol-air temperature (Tsa) and the indoor air temperature:

$\Delta T = Tsa - Ti$ (Tsa is calculated using eq. 2.6)

Table 3.1 Surface resistance of elements (W/m²K)

				normal surfaces	low emittance surfaces
Rsi	inside	walls		0.12	0.30
		ceiling, floor	heat flow up	0.10	0.22
		heat flow down		0.14	0.55
	ceiling, 45°C		heat flow up	0.11	0.23
		heat flow down		0.13	0.38
Rso	outside	walls	sheltered	0.08	0.11
			normal exposure	0.06	0.07
			severe exposure	0.03	0.03
		roofs	sheltered	0.07	0.09
			normal exposure	0.04	0.05
			severe exposure	0.02	0.02

3.1.2 Thermal transmittance

The surfaces of a body also offer some resistance to the heat flow. The inner and outer surface resistances are denoted Rsi and Rso respectively. The reciprocals of these resistances are the surface conductances, hi and ho for inner and outer surfaces respectively. These surface conductances include both convective and radiant components: h = hr + hc. The magnitude of surface conductance depends on the position of the surface, the direction of the heat flow, and air movement.

Heat flow through a building envelope takes place from external air to the air inside the building (or vice versa). Therefore, in order to determine the heat flow, the surface resistances must be added to the total resistance of the different layers of the element; this value is called air-to-air resistance Ra-a. The reciprocal of the air-to-air resistance is the thermal transmittance (U-value) and its unit is W/m²K. Thermal transmittance is the value that best defines the amount of heat that can be transmitted through a component of the building. Low U values indicate a higher capacity to prevent heat flow and, therefore, better insulating performance.

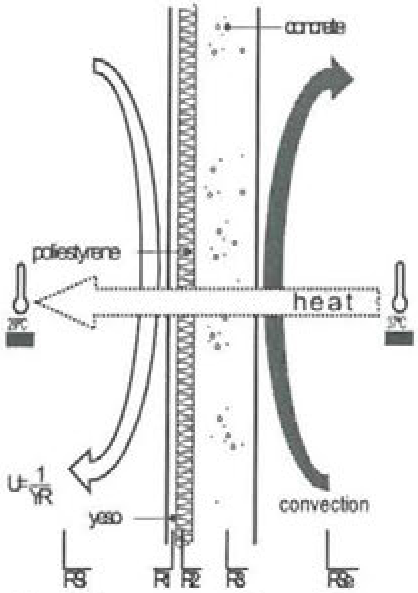


Fig. 3.1 The concept of thermal air-to-air transmittance

$$R_{a-a} = R_{si} + R_{body} + R_{so} \qquad \text{... eq. 3.4)}$$
$$U = 1/(R_{a-a}) \qquad \text{... eq. 3.5)}$$

where:

R_{a-a}	air-to-air resistance of the element (m^2K/W)
R_{si}	inner surface resistance (m^2K/W)
R_{so}	outer surface resistance (m^2K/W)
U	thermal transmittance (W/m^2K)
R_{body}	total resistance of all layers of the body of the element

3.2 Design strategies to reduce conduction heat flow

The two main design strategies discussed in this chapter, that will reduce heat flow by conduction, thus avoiding overheating the building's interior, are obtained from equation 3.1:

a) the use of insulating materials (of a low conductivity, λ) and
b) the use of large thickness (breadth, b) of material to increase resistance but also to generate thermal mass, which also has an insulating effect: dampening the temperature swings

The correct treatment of outer surfaces and the control of microclimatic conditions around the building may also have a positive effect in the reduction of the total heat flow into the building - these are discussed in chapter 6.

The application of these strategies can be affected in an important way by many other factors such as: the use of space, either during daytime, nighttime or mixed; ventilation control or the rate of air exchange; type of thermal control: natural or mechanical; air humidity and temperature; and values of radiation affecting the building.

In buildings with full cross-ventilation, with an envelope that is well protected from solar radiation (sol-air temperature being similar to air temperature), thermal insulation will not serve any purpose, because the indoor temperature will be quite close to the outdoor temperature ($\Delta T \rightarrow 0$) therefore, heat flow by conduction between the exterior and interior will tend to zero.

In buildings where outdoor temperatures and humidity are close to the values for thermal comfort, it will not be necessary to use insulating materials, unless radiation exposure has significant effects on the building. When there is a difference in temperature between the interior and exterior of the building, of at least 4 K, it will be advisable to use techniques for the reduction of conductive heat flow. In naturally ventilated buildings, this difference can be the result of fluctuations in temperature or in ventilation flow, or in solar radiation.

Insulation will be more useful in air conditioned buildings, where indoor temperatures are continuously lower than the outdoors, generally $\Delta T > 6$ K. In this case insulation is practically a must, in order to avoid excessive heat gain, which could heavily increase the air conditioning load.

In the following section the main design strategies for the reduction of conductive heat flow through building envelope elements will be discussed.

3.2.1 Increasing thermal resistance of the element

The use of **insulating materials** is the most basic design principle for the reduction of conductive heat flow though the envelope. These have a low conductivity and high resistivity, in sufficient thickness to obtain high resistance. Heat flow is directly proportional to conductivity; if a material with a conductivity 50% lower than another material is used there will be a 50% reduction in heat flow.

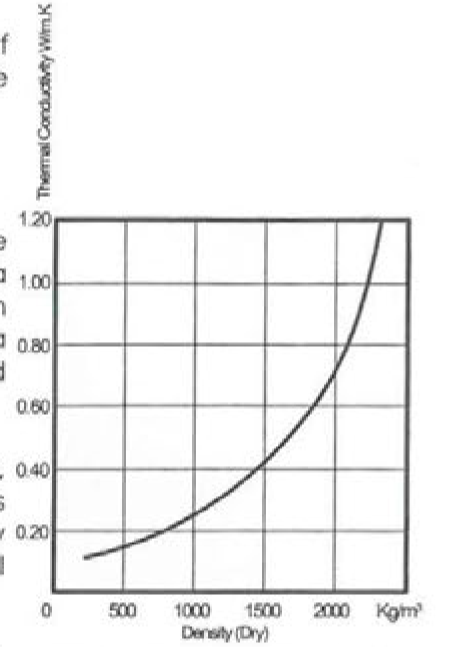


Fig. 3.2 Conductivity as a function of density (dry materials)

Conductivity generally increases as density does. Dense materials, such as metals, are more conductive than light materials, such as polystyrene, but this relationship is not linear (Fig. 3.2). Air has a low conductivity, but if it can move, convective heat transport will increase.

The presence of moisture in the material also increases thermal conductivity, because the water replacing air in the pores has a much greater conductivity; therefore, in warm climates materials should be kept dry, to contain little water (Fig. 3.3).

Many sources (eg. PLEA Note 2) present tables of conductivity and classify materials according to their thermal conductivity. Here the classification proposed by Lavigne (1994) is adopted:

Good conductors: metals: copper, aluminium	50 - 380 W/m.K
Conductors, such as concrete and some bricks	1 - 49.99 W/m.K
Poor conductors, such as wood	0.13 - 0.99 W/m.K
Insulating materials, such as fibres or foams	0.02 - 0.12 W/m.K

Table 3.2 presents some construction materials organized according to this classification.

Table 3.2 Thermal conductivity of some construction materials

Good conductors:	copper	280 W/m.K
	seel	52
	aluminum	165
	structural steel	60
Conductors:	heavy stones	3
	common concrete	2
	compressed earth	1
Poor conductors:	light aggregate concrete	0.14-0.27
	glass	0.8
	wood	0.13-0.2
Insulators:	mineral wool	0.03-0.05
	polystyrene	0.03-0.05

(Gösele & Schule, 1985)

Based on the analysis of conductivity values, the importance of using insulating materials cannot be stressed enough, to reduce heat flow to the interior of a building when $\Delta T > 4$ K. A 50 mm slab of a common insulating material ($\lambda = 0.03$ W/m.K) will act the same way as 3500 mm of common concrete ($\lambda = 2.1$ W/m.K), in terms of insulating capacity (both give a resistance of 1.66 m²K/W).

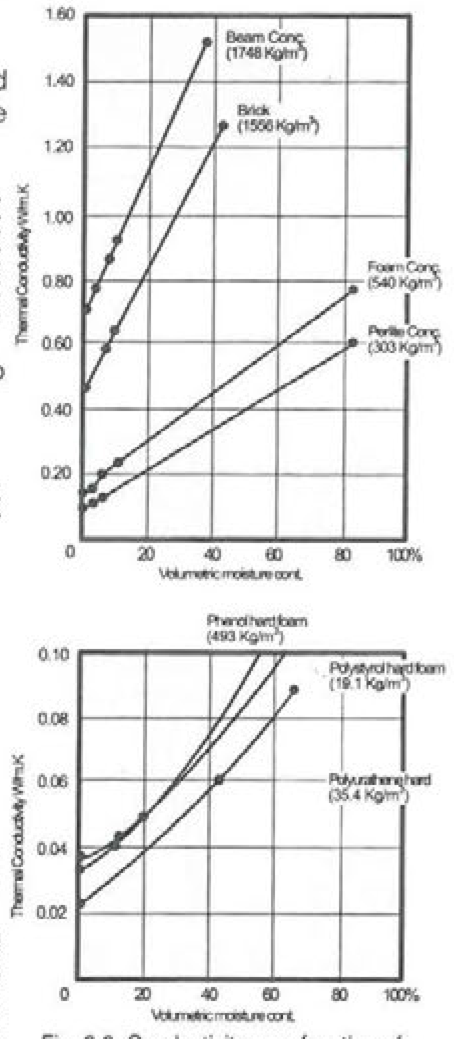


Fig. 3.3 Conductivity as a function of moisture content

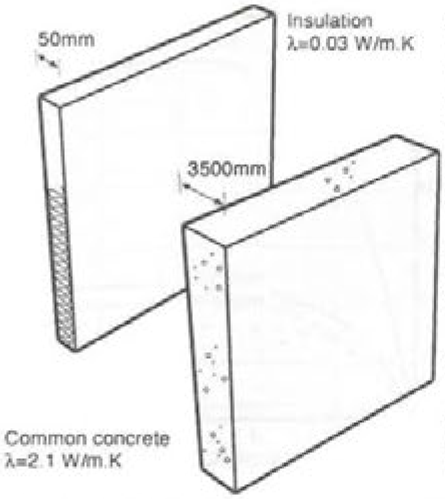


Fig. 3.4 Equivalent thickness of two materials (same resistance), different conductivity

There are constructional elements which are made of several components, or several components and air cavities. This is the very common case of hollow concrete or clay bricks and blocks. For these an equivalent conductivity is calculated by taking a weighted average of cavity and material bridge properties, such as shown by the following example:

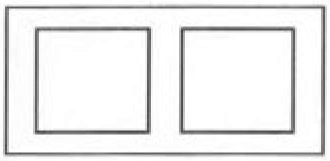
Take a concrete block of 400 x 200 x 200 mm which has two cavities of 155 x 140 mm size, thus all web thicknesses are 30 mm.

data: concrete λ = 1.5 W/m.K   cavity resistance = 0.17 m^2K/W

the resistance of each of the two surface layers is
R1 = R3 = 0.030/1.5 = 0.02 m^2K/W

The average conductance of the middle 140 mm layer must be found first: the cavity conductance is 1/0.17 = 5.8
for the web R = 0.140/1.5 = 0.09,
thus its conductance will be 1/0.09 = 11.1
then weighted average conductance of layer 3:

$$C3 = \frac{11.1 \bullet (30+30+30) + 5.8 \bullet (155+155)}{400} = 6.99$$



A 400x200 mm concr. block
155 x 140 mm cavities
30 mm wall thickness

thus the average R3 is 1/6.99 = 0.14
therefore R_{tot} = 0.02 + 0.14 + 0.02 = 0.18 m^2K/W
as R= b/λ λ = b/R = 0.200/0.18 = 1.1 W/m.K
which is the result required, the notional conductivity of the block.

The same technique can be used to find the U-value of the block: only the surface resistances must be added to the above R_{tot} and its reciprocal will be the U-value.

In walls, and especially in roofs, combinations of materials that generate structural strength and insulating capacity must be used. By using layers of insulating materials good U-values can be obtained with relatively small thicknesses. It is especially important to control thermal gain in elements receiving high solar radiation, such as roofs in low latitudes.

Many authors (eg. Zöld and Szokolay 1997) define thermal insulation as "controlling the flow of heat" and thus distinguish three types of insulation: reflective, resistive and capacitive insulation.

Reflective insulators will be used when the predominant mechanism of heat transfer is radiation and they face an air chamber. They must have low absorptance and high reflectance. The best one is polished aluminum foil.

Resistive insulation is used to control conductive heat flow. This is sometimes referred to as "bulk insulation". Materials used for this are those that have a low conductivity (usually fibrous or porous materials) and insulate depending on their thickness.

Capacitive insulation is also referred to as the "mass effect". The effect depends on the material's density, specific heat capacity and its thickness.

Capacitive insulation has a retarding effect on heat flow. This will be discussed further on.

Cavities. Density is indicative of conductivity (Fig. 3.2). Air is the common substance with the lowest density and conductivity. It is one of the best insulators and is also the cheapest. Therefore the use of an air-filled cavity is recommended as one of the layers of a compound envelope element, either a roof, floor or wall (Fig. 3.5). However, heat flow in cavities (air chambers) takes place not only by conduction through the air: heat reaches the wall of the cavity by conduction and then is transmitted to the opposite wall by convection and radiation. To reduce radiant heat flow across a cavity a reflective insulator (or radiant barrier) should be installed. This will consist of a surface with low emittance and high reflectance on either the warmer (emitter) or cooler (receiver) surface of the cavity, or both.

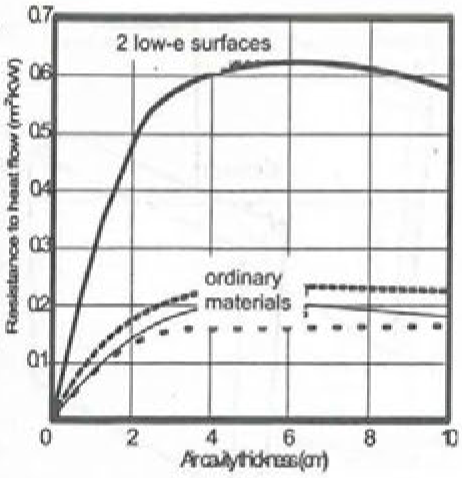


Fig. 3.5 Resistances of cavities as a function of thickness

Resistance of the cavity is not proportional to its width. After 20mm, resistance to the heat flow will remain relatively constant; therefore, increasing the width of a cavity does not have any significant thermal effect. Thermal resistance of a cavity also depends on the direction of heat flow (Table 3.3)

Table 3.3 Thermal resistance of cavities (m^2K/W)

position	flow direction	thickness	resistance
vertical	horizontal	10 – 20	0.14
	horizontal	20 – 500	0.17
horizontal	vertical, up	10 – 500	0.17
	vertical, down	10 – 500	0.21

(Bansal, 1993)

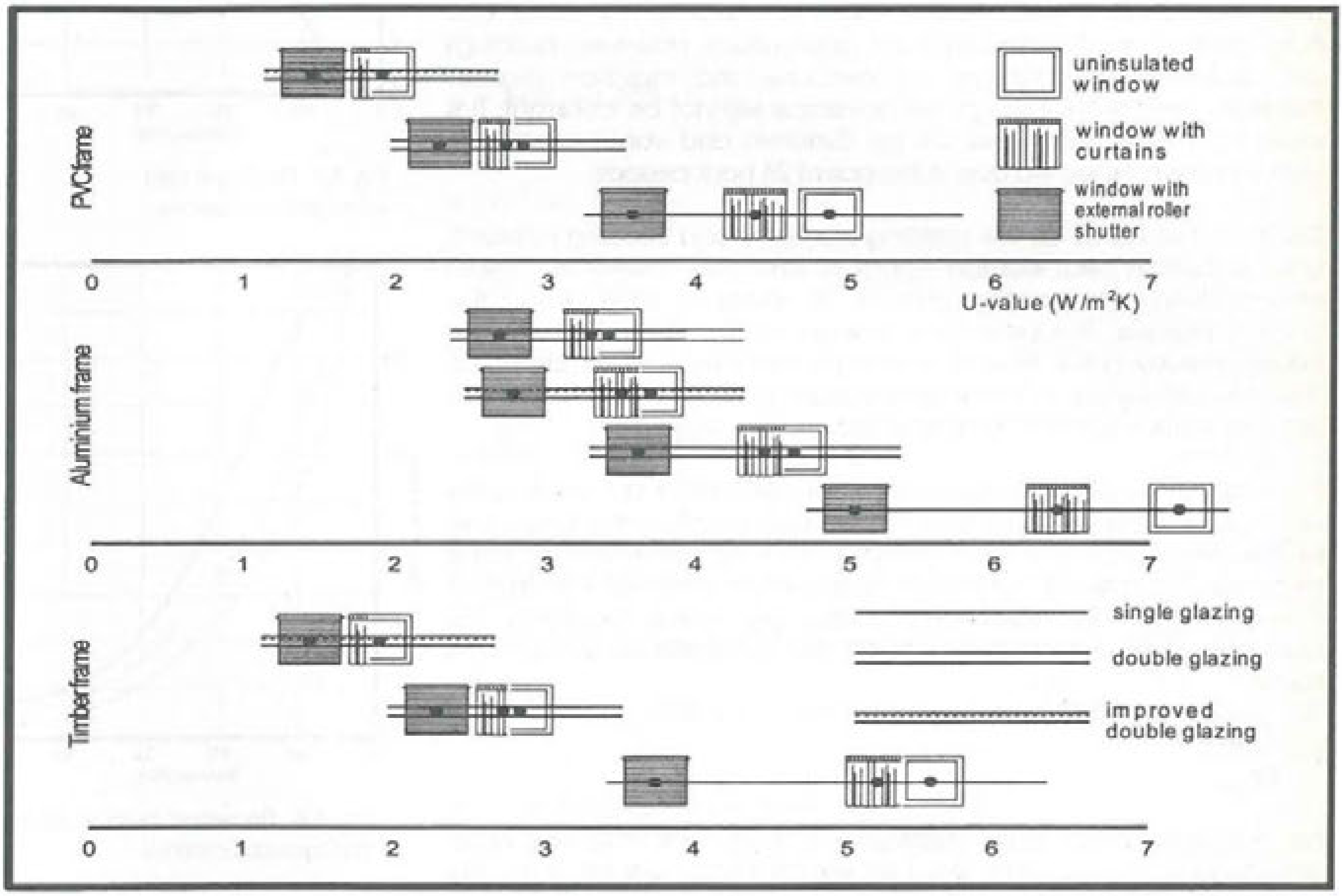
The surface of an element also offers resistance to the heat flow and this **surface resistance** depends on its radiative and convective components. The surface resistance depends on the position of the surface, the direction of heat flow and the velocity of air movement. For horizontal elements the surface resistance is higher when the heat flows downwards and when air velocity is lower. There are may ways to modify the properties of the element's surface (changes in smoothness, texture, inclinations, etc.) and thus increase resistance of the material, which is necessary in hot climates. These strategies are discussed in more detail in the chapter on control of radiation heat gains.

As mentioned in chapter 1, the heat flow though a **window** during daytime, is mainly by radiation and depends mostly on the angle of incidence of solar rays on the glass. However, air-to-air heat transmission by conduction can also be quite significant, especially if the ΔT is large. The magnitude of this will depend on the U-value of the window, which is generally quite high. The importance of a high resistance (low U-value) of windows, in warm climates, is greater when the building is air conditioned and especially when the window is well protected from solar radiation, as in this case the conduction gain will become dominant.

To reduce heat flow by conduction though windows, the following strategies can be applied:

1- use glazing with two or several layers of glass with cavities to act as insulators
2 - use heat reflective glass, which admit less solar radiation
3 - use a low-e surface in the cavity to reduce infrared transmission between two glass panes

Fig. 3.6 indicates comparative values of thermal transmittance for different glazing types and frame materials



From the European Passive Solar Handbook (1992)

Fig. 3.6 Thermal transmittance (U-value) of windows: various glazing and frame types (W/m^2K)

3.2.2 Mass (capacitive insulation) to regulate indoor temperature

When thickness increases, resistance of the component to the heat flow also increases. However, this increase in thickness has a definite limit due to costs and feasibility of construction. For this reason insulating materials are used to block the heat flow rather than regular construction materials of a great thickness. However, insulating materials have low density and low structural strength thus they must be used in combination with other construction materials that give them strength and rigidity. The need arises for the development of multi-layered walls. In walls, and especially in roofs, combinations of materials that provide structural strength and insulating capacity must be used. By using layers of insulating materials good U values can be obtained with a relatively thin layer. It is especially important to control thermal gain in components receiving high solar radiation, such as roofs in low latitudes.

Capacitive insulators act as a function of their thickness, density and their specific heat capacity; they have a delaying effect on heat flow. These will be discussed further on.

The increase of thickness of a layer increases its resistance to heat flow. Resistance is the property taken into account in heat flow calculations based on steady state assumptions. However, buildings are subject to a changing temperature and radiation regime, therefore heat flows through the envelope will not be constant. It is more likely that these flows will be dynamic and vary periodically, with a pattern repeated over subsequent 24 hour periods.

On the other hand, all the building elements and building contents have a certain heat storage capacity and can, therefore, absorb energy during the heating process, to release it later during the cooling process. This process of energy storage and release may cause a delay in the time of maximum and minimum temperature. The time difference in inner temperature peak with respect to the outdoor peak is referred to as **time lag** (ϕ).

If the daily temperature fluctuation is represented by a sinusoidal curve, a levelling of the curve can also take place, ie the amplitude of the curve (distance from average value to maximum values) is reduced. The ratio of the indoor temperature amplitude to that of the outdoor is the **decrement factor** (μ), which expresses the capacity of an element to reduce the temperature swings in a space.

$$\mu = \frac{Ti_{ampl}}{To_{ampl}}$$

For example, if the inner amplitude is Ti_{ampl} = 7K and the outer amplitude is To_{ampl} = 14K, the decrement factor will be 0.50. The highest possible value is one, in elements with no capacity at all to store energy.

Diffusivity is a composite index of material properties:

$$\alpha = \frac{\lambda}{\rho \bullet c} \quad \text{(m}^2\text{/h, if c is in Wh/kg.K)} \quad \text{(m}^2\text{/s, if c is in J/kg.K)} \quad \text{... eq. 3.5)}$$

Where

λ = thermal conductivity (W/m.K)

ρ = density kg/m³

c = specific heat capacity of the material

This is sometimes referred to as temperature conductivity and can be visualised as the surface area of a sphere over which the temperatutre spreads in unit time from a point input. In itself this

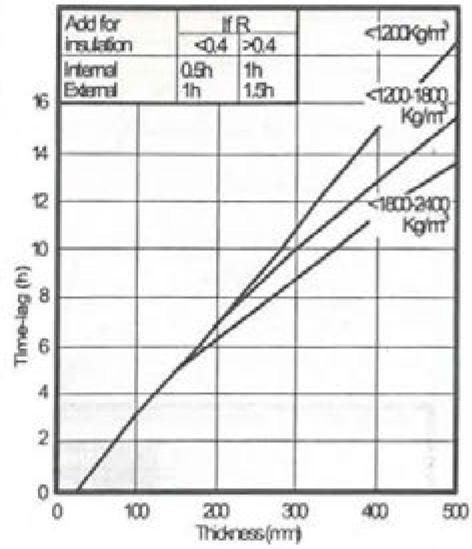


Fig. 3.7 Time lag of solid homogeneous materials

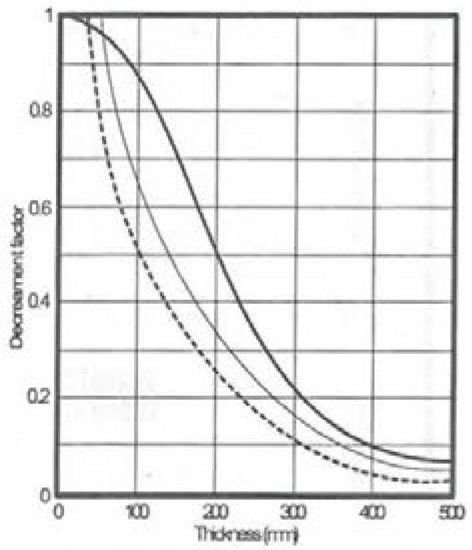


Fig. 3.8 Decrement factor of solid homogeneous materials

quantity is of no practical use, but time lag and decrement factor can be expressed in terms of this α.

Time lag and decrement factor are the most important dynamic thermal properties of an envelope element. For a single layer of homogeneous material these properties can be expressed the following way (Givoni, 1969 quoting Mackey & Wright, 1946):

$$\mu = \exp\left(-b\sqrt{\frac{\pi}{\alpha \bullet 24}}\right) \qquad \text{... eq. 3.6)}$$

$$\sqrt{\frac{\pi}{24}} = 0.362 \text{ thus}$$

$$\mu = \exp\left(-0.362 \bullet b\sqrt{\frac{1}{\alpha}}\right) \qquad \text{... eq. 3.6)}$$

$$\phi = \frac{b}{2} \bullet \sqrt{\frac{24}{\pi \bullet \alpha}} \qquad \text{... eq. 3.7)}$$

and as $\frac{1}{2} \bullet \sqrt{\frac{24}{\pi}} = 1.38$

$$\phi = 1.38 \bullet b \bullet \sqrt{\frac{1}{\alpha}} \qquad \text{... eq. 3.7/a)}$$

$$\mu = \exp\left(-b \bullet \sqrt{\frac{\omega \bullet \rho \bullet c}{2\lambda}}\right) \qquad \text{... eq. 3.6/b)}$$

$$\phi = b \bullet \sqrt{\frac{\rho \bullet c}{2 \bullet \lambda \bullet \omega}} \qquad \text{... eq. 3.7/b)}$$

Where angular velocity of the temperature wave is

$$\omega = \frac{2 \bullet \pi}{24} \quad \text{for a 24-hour cycle} \qquad \text{... eq. 3.8)}$$

b = thickness of element
c = specific heat capacity (Wh/kg.K)

> Note that for eq. 3.5 onwards it is convenient to give the value of c in Wh/kg.K, where the result of both 3.5 and 3.7 is required in hours (the cycle length is also given as 24 h). If c is given in J/kg.K, then the cycle length must be in seconds (24•3600), and α must be in m^2/s.

It can be noted in these equations that a highly conductive material will reduce both the time lag and the decrement factor; whereas a greater density, specific heat capacity and thickness will increase both. For multi-layer elements the decrement factor and time lag also depend on the order of the different layers with respect to heat flow direction and the values of μ and ϕ can be calculated with more complex equations.

Table 3.4 shows the decrement factors of four constructions, each having a U-value of 0.53 W/m^2K.

Table 3.4 Decrement factors of four wall constructions

		surface density: kg/m²	μ
sandwich panel	1 mm aluminium sheet 6 mm insulation 1 mm aluminium sheet	21	0.80
insulated brick wall	20 mm rendering 175 mm brickwork 57 mm insulation 10 mm plasterboard	327	0.26
solid concrete wall	20 mm rendering 400 mm lightweight concrete 15 mm plastering	298	0.03
insulated cavity brick wall	115 mm brickwork 40 mm cavity 55 mm insulation 175 mm brickwork 15 mm plastering	510	0.02

(Hauser, 1981)

Heat storage capacity depends on the mass, and therefore on the volume, density and specific heat of the material. This concept is more easily understood than diffusivity or other physical concepts so the popular term is 'thermal mass'. Stored thermal energy can be determined with equation 3.9 where the capacity to store energy is directly proportional to the specific heat of the constructional element, its thickness, and the temperature difference between the material and the surrounding temperature.

$$Qst = c \bullet \rho \bullet V \bullet \Delta T \quad \text{... eq. 3.9)}$$

where

Qst = heat flow rate into storage (per second) (W)
c = specific heat capacity (J/kg.K)
ρ = density (kg/m³)
V = volume (m³)
ΔT = temp. difference material & surrounding air

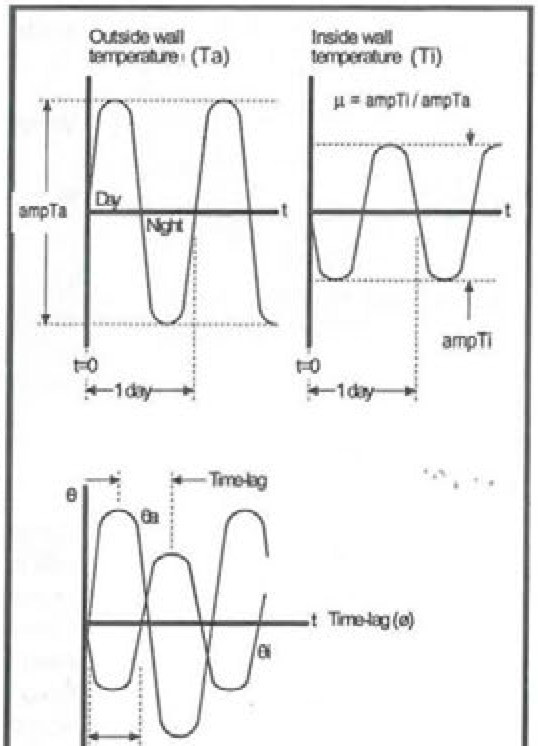


Fig. 3.9 The concept of time lag and decrement factor

Two materials with the same conductivity but different specific heat and density, subject to steady state conditions, constant heat flow, will permit the same heat flow to the interior of the building. However, if the heat flow conditions are periodic, such as in a 24 hour cycle, there can be important differences in relation to the indoor peak temperature and the time of its occurrence. Therefore, two walls of the same U-value exposed to the same heat input but with different mass, can show important differences regarding inner amplitudes and time lag, although the average daily heat flow will be the same. This effect is similar to that of two ponds of different size which take different times to fill up with the same rate of water flow.

If the diurnal temperature variation (the difference between the day-time maximum and night-time minimum) is small, the material will not be able to absorb much energy. Therefore elements with large thermal capacities are not very useful in areas with diurnal variations less than 8 K, such as in warm humid climates. The heavy construction mass is redundant. However, where the diurnal range is large, these materials and elements will help to reduce the indoor temperature peak and the amplitude of variation. When the outdoor temperature varies between too hot during the day and too cool at night, massive construction can be used to reduce the amplitude and make the indoor conditions comfortable day and night.

A material with a high specific heat and density, such as concrete, will store much more heat than a light insulating material; therefore, this concrete will absorb much more energy for the same temperature change and will also release much more energy for the same temperature variation. For example, a concrete wall 300 mm thick will need 2 kWh/m^2 to increase its temperature from 10°C to 20°C (by 10 K), whereas an insulating material of the same thickness will increase by 10 K with only 0.04 kWh/m^2 (Bansal et al. 1994).

In order to use these materials properly it is necessary to know how much mass to use according to the design needs and periodic variations. To determine this quantity, the term active thermal mass is used (Zöld & Szokolay, 1997). In order to do this we must first determine the effective depth, which refers to the depth of penetration of temperature waves during the processes of energy storage and release. This will depend on the period and the conductivity of the storage material. A longer period and a higher conductivity material can make use of a greater thickness of the element.

According to Zöld and Szokolay (1997) this depth of penetration can be calculated mathematically in many ways, but for solid concrete, brick or masonry elements it can be estimated as the least of the following options:

1.- half the total thickness of the construction
2.- 100 mm
3.- the thickness from the surface to the first insulating layer.

This is valid for the 24-hour cycle and was originally proposed for the innermost layer of a wall in a passive solar (direct gain) building, or where the heat input is directly into the space, but it can be applied to situations where the direction of heat flow is periodically reversed (input into storage and release from storage), possibly at the outside surface of an element.

The desirable mass (or thickness) of an envelope element for heat transmission can be best estimated by the use of the time-lag property: it will be the difference between the time of maximum heat input at the outer surface and the time when heat input into the space from the inner face of the element is desirable or can be accepted

Specific admittance (β) of a material (some authors refer to this as 'effusivity') is another composite index of material properties.

$$\beta = \sqrt{\lambda \bullet \rho \bullet c} \quad \text{... eq. 10)}$$

Dimensionally it is $h^{1/2}W/m^2K$ and it is a measure of the ability of the material to absorb heat flow. To obtain the magnitude this quantity for the 24-hour cycle, correct the above by $\sqrt{\frac{2 \bullet \pi}{24}}$ =0.51 ($h^{-1/2}$)

thus the actual **admittance:**

$$a = 0.51 \bullet \beta = 0.51 \bullet \sqrt{\lambda \bullet \rho \bullet c} \text{ (W/m}^2\text{K)} \quad \text{... eq. 3.11)}$$

The **thermal inertia index** (D) of a homogeneous element can be expressed in terms of this a-value:

$$D = a \bullet R = a \bullet \frac{b}{\lambda} \text{ (non-dimensional)} \quad \text{... eq. 3.12)}$$

The correlation of diffusivity (α) and specific admittance (β) is indicative of the thermal properties of different materials. An example of this is given in Fig. 3.10 (after Izard, 1993 and Gonzalez, 1997).

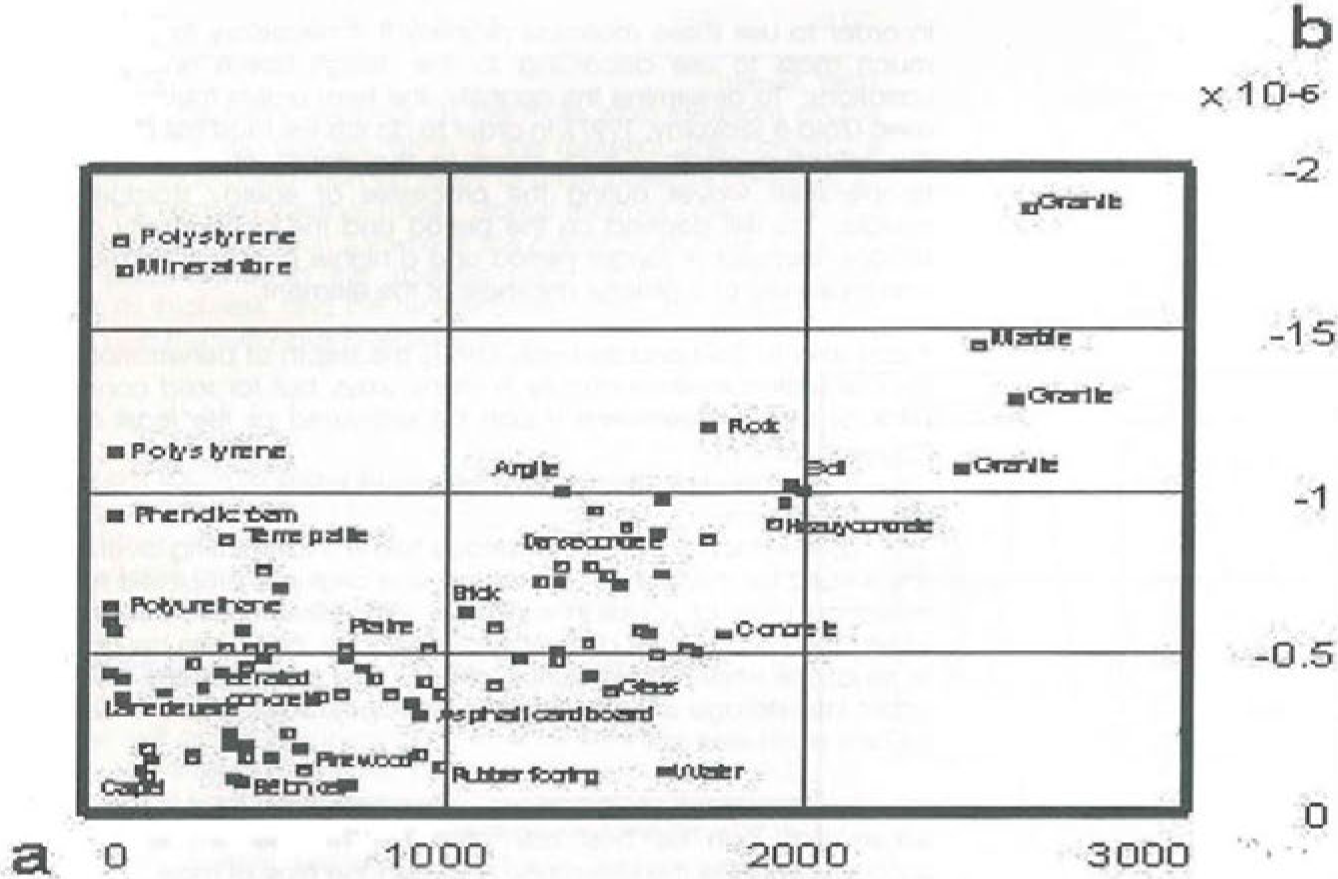


Fig 3.10. Specific admittance (β) vs diffusivity (α) of some common construction materials. (after Gonzalez, 1993)

Such diagrams assist in the selection of materials with appropriate diffusivity and specific admittance in order to reduce amplitude.

It is not possible to make specific recommendations on different combinations of materials on the basis of external conditions alone, since use of space (internal heat gain), solar heat input directly into the space and ventilation conditions should also be taken into account.

In a space designed for daytime use, in a warm climate, it is advisable to use materials that will reduce temperature amplitude (mass effect) to avoid getting too close to daytime outdoor maximum values; materials and elements that will create a long time lag, thus they will delay the heating effect to a time when the space is not in use. For the enclosure of a space for nighttime use it is advisable to select a material with low thermal capacity and short time-lag, thus it will cool down quickly at night. This goal can be reached using a unique and homogeneous material or designing multi-layered walls with suitable materials. In the following paragraphs some recommendations proposed by Lavigne (1994), suitable to reduce thermal amplitude are listed.

If the wall is an homogeneous element:

1 Increase the thickness of the element.
2 Choose a material for the element that has low diffusivity, high specific admittance and low conductivity.
3 Use elements with high specific admittance in the building's interior.

If this homogeneous wall is under considerable thermal load

1 Increase the thickness of the components of the wall.
2 Use thick insulating walls, with high internal admittance.
3 Reduce solar radiation absorptance and protect from solar radiation.

If the wall is an element with two layers of different materials:

1 Place a high admittance layer on the inside and the insulating layer on the outside, this way the mass is protected from the exterior, thus avoiding accumulation of energy from incident radiation or high temperatures and promoting accumulation of "cold" from inside the building.
2 Interior elements (eg partitions) need not be of high admittance although that may be helpful.

If the wall, with two layers of different materials, is subject to large thermal load thermal charges, we should:

1 Locate the high admittance layer in the inside and the insulating layer on the outside.
2 Increase the thickness of the components of the wall
3 Reduce solar radiation absorptance and protect from solar radiation.

According to measurements carried out (Gonzalez, 1993) the effect of high diffusivity on the decrement factor is much more important than the effect of high admittance (for identical β values there can be 80% variation due to diffusivity, whereas the effect of admittance with constant diffusivity does not go beyond 23%). Therefore, with multi-layer elements a much better behaviour can be obtained than with homogeneous ones. Gonzalez (1993) proposes combinations of specific admittance and diffusivity depending on the use of the space and the form of thermal controls.

Table 3.5 Recommendations for diffusivity, α and specific admittance (effusivity), β according to space use and control

building use	air conditioned building 1 air ch/hour	1-20 air ch/h	free running building 1—20 air ch/h
day time 7—19 h	α low β indifferent	α low β indifferent (low)	α low β indifferent (low)
night time 19 – 7	α high β low		α indifferent (low) β low
continuous 24 hours	α low β low		α low β low

(Gonzalez, 1993)

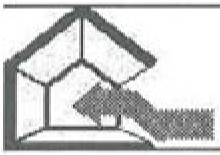
3.2.3 Other strategies to reduce conduction heat flow

In addition to the two strategies (insulation and mass) mentioned above, there are others that will also reduce the conduction heat flow, but they are not as effective or are more complex to apply. Nevertheless these will also be discussed.

Reduce surface area. If the area in contact with the exterior is reduced, heat flow through the envelope will also be reduced: the value of A in equation 3.1 is reduced therefore Q is also reduced. Buildings with a lesser area in contact with the exterior are more efficient in the control of heat by conduction. However, if ventilation exchanges are considered (see chapter 4), when Ti > To a larger building surface will be more favourable, to allow the introduction of more air to the building. Generally, it is difficult to modify the surface area of a building significantly.

Reduce temperature difference. If the indoor temperature limit is set as high as acceptable, the ΔT is reduced. If landscaping techniques are applied to reduce the outdoor air temperature, the ΔT is also reduced and, as a result, Q, the heat flow to the interior is reduced. Some of these microclimatic design techniques that allow outer temperature reduction are described in chapter 6.

4 VENTILATION / INFILTRATION HEAT GAIN CONTROL



Heat transfer by convective and mass transfer effects happens due to the presence of a temperature difference between the outdoor environment and the indoor s of a building. This temperature difference causes a flow of heat from the higher temperature zone to that of lower temperature. Much of this heat flow is due to the air flow generated by ventilation (natural or forced) and infiltration. The relationship between the indoor and outdoor temperatures and the air flow can be understood clearly in the following equation, which is used to estimate the heat flow rate due to ventilation effects:

$$Qv = qv \bullet (To - Ti) = \rho \bullet c \bullet vr \bullet (To - Ti) \qquad \text{... eq. 4.1)}$$

where:

Qv sensible heat transfer rate (W)
qv $= \rho \bullet c \bullet vr$ = ventilation conductance (W/K)
ρ density of air (kg/m^3)
c specific heat capacity of air (J/kg.K).
The product $\rho \bullet c$ is taken as 1200 J/m^3K for places under 500m.
vr ventilation (volume flow-) rate (m^3/s)
To outdoor air temperature (°C)
Ti indoor air temperature (°C)

And the volume flow rate is estimated as

$$vr = \frac{N \bullet V}{3600} \quad (m^3/s) \qquad \text{... eq. 4.2)}$$

where:

N number of air changes per hour (ac/h)
V volume of internal space (m^3)

as $\frac{1200}{3600} = 0.33$

$$Qv = 0.33 \bullet N \bullet V \bullet (To - Ti) \qquad \text{... eq. 4.3)}$$

Depending on climatic, micro-climatic and seasonal variations at the location of the building, and on the daily variation of temperature, there will be situations where To is higher than Ti or vice versa. In cases where To > Ti, there will be heat gain to the building's interior, which will be greater when the temperature differences are larger and when the ventilation rate is greater. If, on the contrary, To < Ti, there will be a heat flow to the outside, cooler outside air entering and cooling the space.

To illustrate the above, two situations are assumed and the heat flow rates are estimated:

1 with a temperature difference of 5 K (To > Ti) and -5 K (To < Ti), assuming temperatures of 32°C and 27°C respectively.
2 with a 10 K temperature difference (To > Ti) and -10 K (To < Ti), assuming temperatures of 34°C and 24°C respectively.

For both situations, four different hourly air change rates are assumed for an internal volume of air of 100m³. The results are summarised in the following table:

Table 4.1 Ventilation heat gains and losses (an example)

		To > Ti		To < Ti	
N	vr	ΔT = 5 K	ΔT = 10 K	ΔT = 5 K	ΔT = 10 K
ac/h	m³/s	Qv (W)	Qv (W)	Qv (W)	Qv (W)
0.2	0.006	36.6	73.2	- 36.6	- 73.2
0.5	0.01	61	122	- 61	-122
1	0.03	183	366	-183	-366
2	0.06	366	732	-366	-732

As ventilation can result in either heat gain or heat loss, it is important to control it according to requirements. For cooling many sources* (eg. Cook, 1989) recommend the following:

- close and seal the building when the outdoor temperature is higher than the indoor (To > Ti)
- open the building when the outdoor temperature is lower than the indoor temperature (To < Ti)

4.1 Seal the building when To > Ti

When ventilation causes a heat transfer to the building's interior (heat gain), the building should be completely sealed. In other words, doors and windows should be closed and other openings (services penetrations of the envelope, joints between structural elements, among others) should be sealed to prevent the entry of hot air by ventilation and infiltration.

However, the implementation of this measure must still ensure a minimum of fresh air supply, an air change rate around 0.5 to 1.0 ac/h to ensure healthy air conditions by eliminating pollutants or toxic elements produced by man or indoor processes.

The rate of involuntary air change rate, or infiltration rate, depends on the design and construction of the building, and on the location. In buildings designed for air conditioning infiltration is reduced to a minimum thus the minimum fresh air supply must be ensured by some means. It is suggested that 0.5 ac/h should be allowed for, as this is both desirable and it is difficult to seal the building to reduce it below this value.

Some infiltration rate values have been obtained experimentally by case studies in different parts of the world and with different building types. The results vary between 0.2 and 2 ac/h. The estimation of infiltration requires complex computations, as the behaviour of fluids in motion is to be determined, which is generally turbulent (Achard, 1986).

*Florida Solar Energy Center; Kusuda, 1981 and 83; Kammerund et al. 1984; Neeper and McFarland, 1982; Chandra and Kerestecioglu, 1984; Givoni, 1968 and 1976;; ASHRAE, 1993—all as referenced in Cook, 1989.

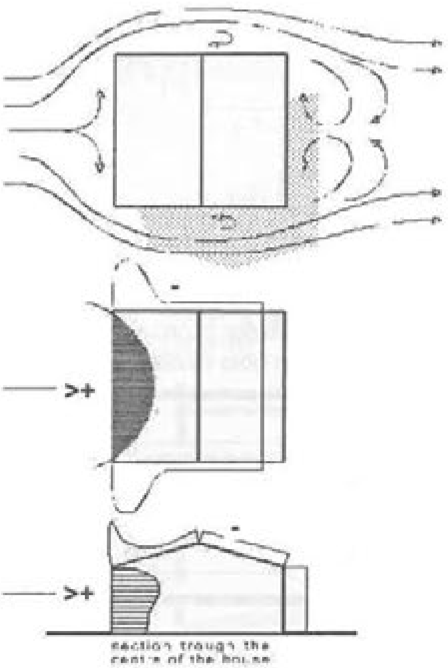


Fig. 4.1 Distribution of pressure fields in a building

The rate of infiltration is also very variable over the 24-hour period and its magnitude depends mainly on three climatic factors:

- the velocity and direction of the wind which produces different pressure distributions and fields around the building (see Fig. 4.1)
- the "pulsation" effect, which produces some air infiltration rates around windows or doors completely sealed, as a consequence of pressure distribution changes resulting from changes in the direction and speed of the wind.
- the temperature differences between the outdoor and indoors and the different spaces within the building, which cause variations in air density. This density difference (lower when the air temperature is higher) generates pressure changes and rising air movements ("stack" effect), at very low speeds or pressure differences between lower and upper parts of the building.

If the building is closed and sealed the interior of the building may become uncomfortable, mainly due to the occupants' emissions or internal processes, it may be necessary to apply some measures to ameliorate the conditions. These actions or measures are as follows:

- Increase internal air velocity, using mechanical means: portable or ceiling mounted fans, with speed controls to allow adjusting of the air speed according to comfort needs.
- Use dehumidifying equipment to reduce humidity generated by equipment and persons, especially in warm-humid climates.
- Keep kitchen and laundry areas isolated from the rest of the building, and extract humidity produced by localized exhaust ventilation.

If, apart from humidity increases, there are also temperature increases above levels tolerated by man, the recommendation is to use air conditioning appliances during this period of time.

4.2 Open the building when To < Ti

This recommendation originates from the need to dissipate hot air from inside the building and to reduce the internal temperature by introducing lower temperature external air. For this reason the following is recommended:

- In hot dry or arid climates dissipate the heat stored in the building fabric, particularly during the night, when the outside temperature is lower. This cooling can be achieved by the opening of doors and windows or through controlled wind induction (ASHRAE, 1993). This would provide a cool fabric for the hot part of the day, to absorb heat, whilst the building is closed.
- In warm humid climates maximize air speeds inside buildings, especially at the occupied areas and levels, to produce physiological cooling and thus to obtain better comfort conditions (Cook, 1986). An increase in air speed promotes evaporative cooling of the skin (removing the saturated air layer adjacent to the skin), reduces thermal resistance of the air film around the body and diminishes the increase of convection heat gain, when the temperature of the air is higher than the temperature of the skin (≈34°C). (Achard, 1986)

In warm humid climates, cross ventilation constitutes the most effective strategy to reduce heat inside the building, both by increased ventilation rates (air exchanges) and by creating air velocities sufficient for physiological cooling at the body surface.

Such cross ventilation may result from the effect of wind producing positive pressure zones on the windward side (air entry openings should be provided in this zone) and negative pressure zones on the leeward side to produce a suction effect (air outlet openings should be located here) (See Fig. 4.2). Comfort may be achieved by air velocity even when the air temperature is above the comfort limit.

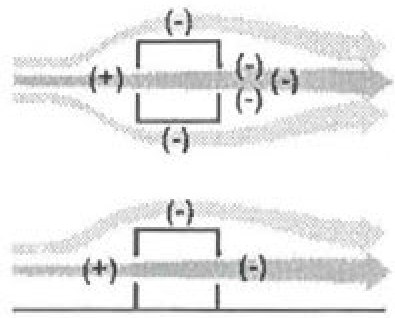


Fig.4.2. Distribution of pressure fields in a building with cross ventilation

The utilisation of cross ventilation (rather than the use of mechanical cooling) can represent important energy savings in the building. According to results obtained in the Florida Solar Energy Center, with air speeds of 0.57 m/s and 0.85 m/s, reductions of the perceived internal temperature between 2.2 to 2.7 K were attained (Cook, 1986). Other research suggests that a 1 m/s air velocity at the body surface creates a perceived cooling effect of 3 K and 1.5 m/s up to 5 K.

When the intention is to make an efficient use of natural ventilation, the building must be designed (or redesigned), in full knowledge of the climate. Besides temperature, humidity and solar radiation conditions of the locations it is necessary to know the wind pattern, both the speed and the direction, as well as the frequency distribution (especially during the overheated periods). Then the building can be positioned and shaped accordingly. The factors influencing such design will be discussed in the following paragraphs.

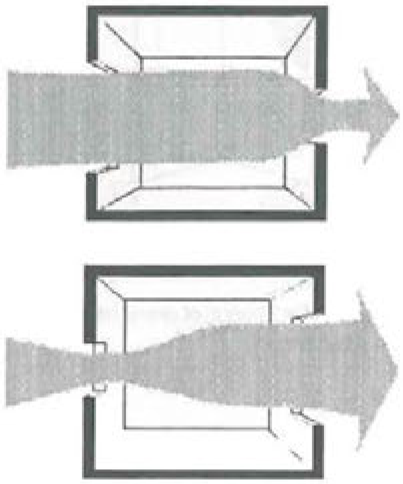


Fig. 4.3 The effect of inlet and outlet

4.2.1 The building and the internal space ventilation

Different wind tunnel studies carried out on scale models have established the effect of space geometry, location and shape of the openings on cross ventilation, which must be considered at the design stage to optimize ventilation in buildings. These studies (Texas A&M, as quoted by Cook, 1986) recommend the following:

- There should be an inlet opening or window and an outlet or exit, to maximize wind speed.
- There should be an air outlet larger than the inlet to obtain maximum speeds in areas to which the inlet stream can be directed (and wind speed averages in the internal space are best when both openings are as large as possible) (Fig. 4.3).
- Location of the outlet does not significantly affect the air flow pattern (see Fig. 4.4).
- Location of the inlet does affect the internal air flow pattern (see Fig. 4.5).

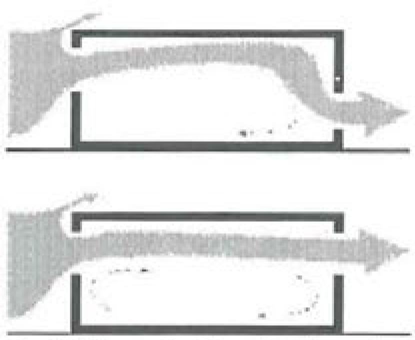


Fig. 4.4 Change in exit opening does not affect air flow pattern

Givoni (1969), suggests that the best ventilation conditions in the internal space (in terms of overall air movement and avoidance of stagnant air pockets) are obtained when the air flow changes direction inside the room (see Fig. 4.6). The first preference is to have a single row of rooms, each room with an inlet and outlet opening (Fig. 4.7).

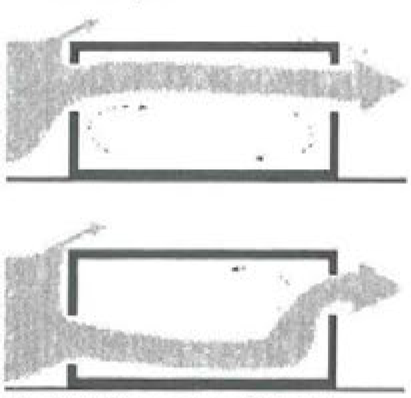


Fig.4.5 Air flow pattern affected by inlet opening position

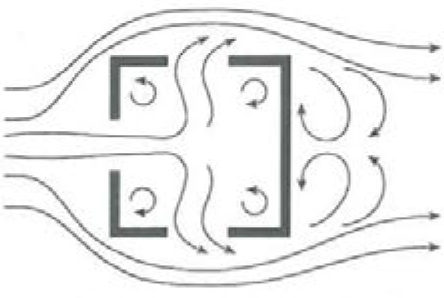


Fig. 4.6. Change of air flow direction with lateral openings

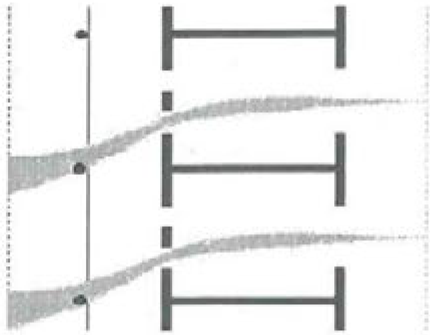


Fig. 4.7 Single row of rooms for cross ventilation

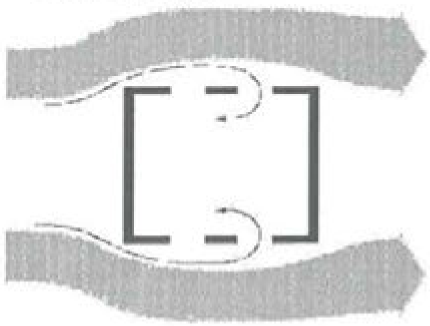


Fig. 4.8 Twin windows in walls sideways to wind direction

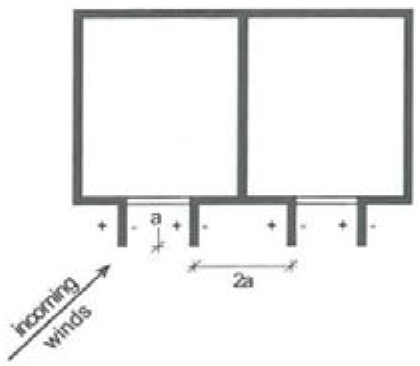


Fig. 4.9. Suggested wing-walls to windows for rooms with one external wall only

If there are internal walls these should be closer to the outlet opening and should have openings (doorways) at least the same size as the windows. When the room has one external wall only it is suggested to have two windows, at least, placed in the extremes of the wall: These will permit some internal flow (Fig. 4.8).

The benefits of the window placement depend also on the relative external relationships and on the presence of any obstructions.

It has also been demonstrated, (Givoni, 1969) that the best ventilation does not always occur when the window is perpendicular to the wind direction (i.e. the window is facing the wind) (see Table 4.2). It is suggested that the angle between the wall and wind direction should be between 20 and 70 degrees .

Winds determine the following:
- perpendicular winds without cross ventilation in a room produce a low average win speed and are liable to cause buffeting,

- perpendicular winds with cross ventilation in a room produce an average wind speed and internal maximum speed double that with window in one side only.

- With windows in one wall only added vertical fins or wing-walls can be placed on both sides of the window to create pressure differences and induce some ventilation. (see Fig. 4.9) (Givoni, 1969, Cook, 1989).

Table 4.2. The effect of window location and wind direction on speed (as % of external wind speed)

opening width as fraction of wall length: inlet	outlet	perpend wind incidence	oblique	perpend wind incidence	oblique
1/3	1/3	35	42	45	37
1/3	2/3	39	40	39	40
2/3	1/3	34	43	51	36
2/3	2/3	37	51	-	-
1/3	3/3	44	44	51	45
3/3	1/3	32	41	50	37
2/3	3/3	35	59	-	-
3/3	2/3	36	62	-	-
3/3	3/3	47	63	-	-

(Buffington, 1981)

The shape of the windows also affects internal air flow; windows with horizontal proportions generate higher indoor air velocities and catch a larger range of wind directions than vertical shapes (Sobin, 1981 / Cook, 1989). Such horizontal windows are particularly beneficial in locations where changes in wind pattern are more prevalent (see Fig. 4.10)

In all cases windows should be accessible and operable so that users can control and direct winds according to ventilation needs.

Obstructions, such as internal divisions should not form barriers to inlet openings. In any case, divisions or partitions should be perforated, be less than full height or have openings (e.g. doorways) to permit unrestricted air flow. Fly screens completely covering windows and other openings, also reduce wind speed (Givoni, 1969, Cook, 1986). Wire or cotton meshes are the worst. Smooth nylon (or other plastic) screens offer the least resistance.

Generally, if the building is to have natural ventilation, windows and doors should be placed in the longer facades (bigger surface area), which are to face towards the prevalent wind direction. It is recommended to have windows of at least 15% of the floor area, to provide the necessary internal air exchanges and air movement for comfort. However, with large occupation densities or internal heat gain opening areas should be much larger.

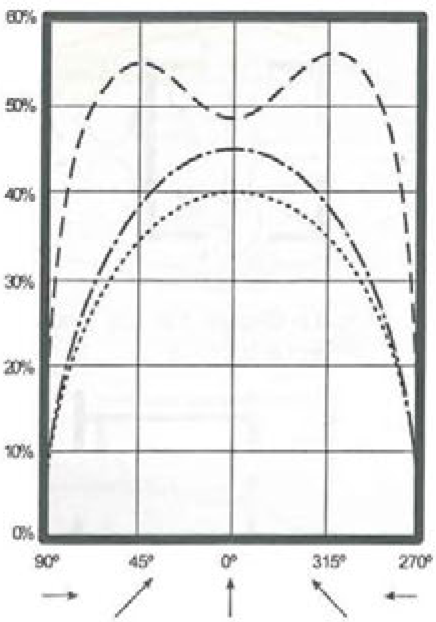


Fig. 10 Indoor air velocity (% of outdoor) as a function of wind direction

4.2.2 Building shape and ventilation induction

In warm-humid climates the aim of ventilation is to provide maximum penetration and significant indoor air velocities. In hot dry climates the control of ventilation (closure during the day, ample ventilation at night) is the task. Among the main elements of the building that affect the ventilation pattern are: the height, and length (across the wind direction) and width (the plan dimension parallel with the wind direction) of the building, the width-length relationship (aspect ratio), roof slope, eaves, orientation and openings. In relation to these elements it is important to consider the following (Evans, 1991, Givoni, 1976):

- An increase in the length of the side facing the wind enlarges the surface exposed to the wind whilst the depth of the wake (the 'wind shadow') remains constant.
- An increase in the building's height provides higher speeds in the upper levels, but also increases speeds in the spaces located in the ground floor. This is particularly so in buildings with free floor areas, or buildings elevated on stilts (or posts or columns).
- A decrease in the width-height relationship increases the depth of the wake, the 'wind shadow'..
- If the slope of a monopitch roof is facing the wind with an angle of slope of more than 30°, there will be an increase in the depth of the wind shadow.
- When the roof slope is away from the wind (up to 30°), any increase of the wind shadow will be very small. For greater slopes there will be no further increases.
- If the slope of a gable roof is increased, the height and depth of the wind shadow (the negative pressure zone) are also increased.
- Eaves on the leeward side have little effect on the wind shadow, but they contribute to induce ventilation when facing the wind. Eaves and canopies over the window deflect the indoor air flow upwards, away from the occupied zone. That is why such devices should be separated from the wall to improve the indoor air stream direction and help penetration. As the angle between the wind direction and the length of the building (regardless of the shape) approaches 90 degrees (normal incidence), the wind shadow will also increase.

The following considerations should also be taken into account:

- If the inlet and outlet openings are at the same level and near the ceiling, only a small part of the air flow will reach the occupied level.
- Openings in gable roofs (at the ridge) are useful in open plan buildings, because they produce suction effects, which allow hot air exit).
- Open staircase inside the building can be used to promote the "stack" effect.
- The "stack" effect requires bigger vertical distances. The bigger the vertical distance, the greater the ventilation.

4.2.3 The surroundings of the building and ventilation.

It is important to take advantage of the topography, landscape and the surroundings of the building to re-direct the air flow and ensure a maximum exposure to the breeze (ASHRAE, 1993). This can be achieved using garden elements (trees, bushes, fences or low walls, among others) to re-direct the breeze and avoid stagnant air pockets. These garden elements can be placed:

- very near the building and windows, they may reduce wind speed, modify air's flow pattern, but they can also be used to increase the air speed, depending on their location and porosity levels (Givoni, 1969).

- with oblique wind incidence, and placed at the sides of the window away from the wind they can act as a wing-wall, create an increased positive pressure and increase air flow through the building.

We must also consider that, under tall trees (approximately 9 m high, 7.5 m crown spread and trunk height of 1.5 m) wind speeds can be increased, as the trunk causes little resistance to the wind compared with the crown above, which is forcing some of the air flow downwards.

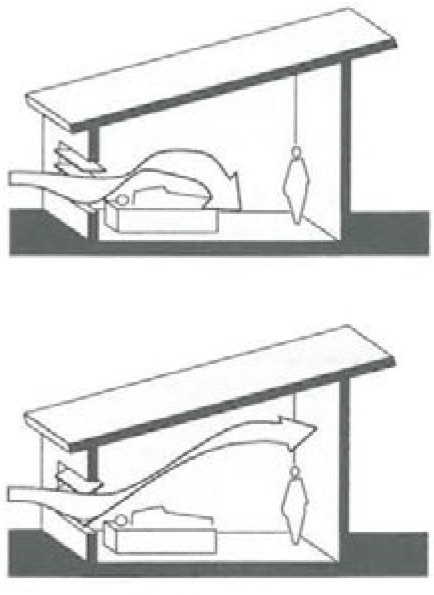


Fig. 4.11 Wide louvres can direct indoor air flow according to the need and use of space

4.3 Estimation of indoor air flow rate

If the wind velocity is known, its pressure can be estimated as

$p_w = 0.5 \bullet d \bullet v^2$

where d = density of air, which varies with temperature at 0°C d = 1.293 kg/m³

At any temperature T it is $d_T = 1.293 \bullet 273/T$

where T is absolute temperature in °K : (°C + 273)

but it is often taken as 1.224 kg/m³ (corresponding to 15°C)

v = air velocity in m/s

Thus generally

$$p_w = 0.612 \bullet v^2 \quad \text{... eq. 4.4)}$$

For a building surface or a window this must be multiplied by a pressure coefficient, c_p

typical values of which are

on windward side $c_{pW} = 0.5$ to 1

on leeward side $c_{pL} = -0.3$ to -0.4

The higher values are applicable if the house faces an open field or it is in a coastal location, the lower ones relate to a densely built-up suburban location. For high rise or non-typical situations these pressure coefficients must be found from wind tunnel studies.

Cross-ventilation is driven by the wind pressure difference

$$\Delta p_w = p_w \bullet (c_{pW} - c_{pL}) \quad \text{... eq. 4.5)}$$

The resulting volume flow rate will be

$$vr = 0.827 \bullet A \bullet c_e \bullet \sqrt{\Delta p_w} \quad \text{... eq. 4.6)}$$

where A = effective area of openings

c_e = effectiveness coefficient

The values of this c_e are:

from window in one wall only, no cross ventilation: 0.1

to full cross ventilation, equal inlet and outlet, no partitions 1.0

(interpolate between these two values for partial internal obstructions)

eg. if v = 3 m/s

$c_{pW} = 0.9$

$c_{pL} = -0.4$

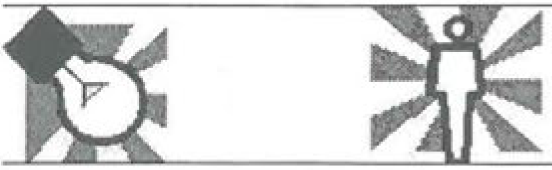
then $\Delta p_w = 0.612 \bullet 3^2 \bullet (0.9 - (-0.4)) = 0.612 \bullet 9 \bullet 1.3 = 7.16$ Pa

and if A = 3 m²

$c_e = 1$ (full cross ventilation)

then $vr = 0.827 \bullet 3 \bullet 1 \bullet \sqrt{7.16} = 6.64$ m³/s

5 REDUCTION OF INTERNAL GAINS



To prevent overheating in buildings it is also important to consider that there are also heat sources inside. These include people, electrical equipment or domestic appliances, as well as electric lighting. The heat contributions from these sources can mean substantial increases in the temperature inside a space, that is undesirable under warm environmental conditions, both dry and humid. The relevant recommendations can be grouped under three headings:

- minimize heat gains from occupants
- minimize the heat generated by equipment
- minimize the heat output of lamps

5.1 Minimize the heat gains from occupants

The human body, just like any biological machine, consumes energy to carry out the necessary chemical transformations (food oxidation) to stay alive and dissipate excess heat. It is estimated that from the total consumed energy, only 20% is used by the body to produce mechanical work (both movement and internal body processes), while 80% is dissipated as heat. This avoids excessive warming, since for the human body it is vital to maintain an internal temperature of around 37°C. (La Roche, 1992). This continuous bodily energy processes are known as metabolism. Metabolic heat production will vary according to the activity level of the person. Table 5.1 shows that metabolic heat production increases with more intensive activity.

Table 5.1 Metabolic rate at different activities

activity		metabolic production per unit body surface W/m^2	met units	average person W
at rest, lying		46	0.8	80
at rest, sitting		58	1.0	100
sedentary activity (home, office, school, laboratory)		70	1.2	120
light activity, (shops, light industry)		93	1.6	160
medium activity, (housework, machine tool work)		116	2.0	200
walking at	2 km/h	110	1.9	190
	3 km/h	140	2.4	242
	4 km/h	165	2.8	285
	5 km/h	200	3.4	350

ISO 7730 (1994)

The energy required for mechanical work (W) will also vary according to the activity, being zero when there is no mechanical work, at rest, and can increase to over 400 W with very intense activity. The energy output in mechanical work should not exceed 25% of the total metabolic rate. (Parsons, 1993)

Heat dissipation from the body takes place through:

- the skin, by convection, radiation and evaporation (perspiration and moisture diffusion)
- the lungs, by respiration: mainly convection and evaporation.

The process of heat dissipation from the body constitutes a heat gain for the interior space of the building. The process will occur if the temperature of the air and that of the surrounding surfaces are lower than the temperature of the skin (≈34°C). Above this temperature, the body will gain heat, and will try, through self-regulating mechanisms (increase the skin temperature, and increase evaporative cooling by sweating) to maintain body temperature and achieve thermal balance.

The following equation (ASHRAE, 1993) clearly illustrates this situation:

$$Qsk + Qres = M - W \qquad \text{... eq. 5.1)}$$

where:

Qsk = heat loss rate through the skin
= C + R + Esk
where C = convective heat loss
R = radiant heat loss
Esk = evaporative loss (perspiration, diffusion).

Qres = heat loss rate through respiration
= Cres + Eres
where Cres = convection heat loss in respiration
Eres = evaporative heat loss in respiration.

M = metabolic heat production rate

W = rate of heat generation by mechanical work

(for a more detailed discussion see PLEA Note 3)

In warm environments, where temperatures are above 26°C, any additional heat gain will add to discomfort. If there are three persons, sitting, in a room, this would add heat to this environment at the rate of some 240 W (see Table 5.1), which will significantly increase the air temperature, and will also increase humidity by respiration and skin evaporation.

For these reasons it is important that in warm climates the environmental control strategy should be chosen to suit the use or function of each space, the number of persons occupying these spaces, and activities these persons are to be engaged in. For spaces occupied by many people, or people engaged in vigorous activities, the use of natural ventilation alone, especially at low speed or unreliable winds cannot be recommended.

5.2 Minimize heat output by equipment

Electrical, gas or steam appliances also generate and transmit heat to the interior. The heat output rate will depend on type of appliance (motor) and on its efficiency.

According to ASHRAE (1993), the equation to calculate heat gain from electric motors in air-conditioned spaces is:

$$Q_m = \frac{P}{\eta} \bullet F_U \bullet F_L \qquad \text{... eq. 5.2)}$$

where

Q_m = motor heat output rate (W)

P = electrical power of motor (W)

η = the efficiency of the motor, as a decimal fraction (< 1.0)

F_U = use factor of the motor, the fraction of time it is used in intermittent operation (1 (one) for continuous operation)

F_L = the motor's load factor, 1.0 or decimal fraction < 1.0

For other heat gain equations see ASHRAE, 1993.

As a general guide, the following table shows the rated power of some electrical appliances in domestic use. These numbers multiplied by the duration of use (in hours) will give the energy consumption in Wh (watt-hours). In all cases the total electrical power can be taken as heat gain, since the mechanical work performed will also be converted to heat.

Table 5.2 Electric equipment in domestic use (rated power)

appliance	power	appliance	power
vacuum cleaner	600 – 1200	sewing machine	≈ 120
coffee percolator	600 – 900	typewriter	≈ 140
water heater	2400 – 3600	personal computer (incl.VDU)	≈ 800
twin hotplate	1200 – 2400	printer	60 – 140
four hotplate cook-top	5000 – 6000	television	100 – 240
oven	3000 – 4000	room air conditioner	1200 – 4800
microwave oven	≈ 1300	fan	80 – 120
cooker (range, stove)	≈ 10 000	ceiling fan	60 – 250
refrigerator, 1 door, manual	150 – 260	washing machine, twin tub	≈ 500
2 door, auto defrost	350 – 400	automatic	800 – 900
2 door, frost free	500 – 600	clothes drier	1500 – 2400
freezer chest	200 – 300	hair drier	600 - 1200
jug or kettle	≈ 1800	dishwasher, cold water	≈ 2000
food mixer, blender	200 – 600	hot water	≈ 1000
toaster	≈ 1500	iron	≈ 1000

In hot climates (especially warm-humid climates), where it is necessary to minimize the heat gains from electrical equipment, the following can be recommended:

- to use appliances correctly: switched off when not in use and use them at times when the indoor temperature is its lowest
- to position these appliances in the open or outside of continuous human occupancy
- ventilate separately the heat emitting part of appliances (eg. condenser coil at the back of refrigerators, or use an exhaust hood over the cooker/stove)
- to maintain the equipment in good order and to avoid excessive heat generation due to lack of cleaning and maintenance
- to acquire or buy equipment of the size appropriate to the needs; the use of high efficiency equipment is preferable; oversized equipment run at partial load is very inefficient and generates more heat than necessary.

5.3 Minimize heat contribution from lighting

In many hot humid countries incandescent lamps are still often used in inhabited spaces, in spite of the fact that different types of high efficiency lamps are available, with reduced heat generation, consuming less energy, and with a longer useful life.

In incandescent lighting 90-95% of the consumed energy is emitted as heat (some 72% by radiation, 12% by convection and 6% conduction from the lamp and lamp holder). Only 5-10% is emitted as light (Indriago, 1997). In fluorescent lamps (including compact fluorescents) only about 70-75% of the energy consumed is emitted as heat and 25-30% as light.

Table 5.3 Comparison of incandescent and fluorescent lamps

Characteristic	incandescent	fluorescent
Light emission	900 lumen	900 lumens
Energy consumption	75 W	13 W
Luminous efficacy	12 lm/W	69 lm/W
Heat emission	90 % (67W)	75 % (10W)
Useful life	1 000hours	8.000 hours
Energy saving	0	75 %

(Habitar, 1993)

It is important to note (ASHRAE, 1993) that only a part of the heat generated by lamps is emitted by convection, which can be easily dissipated by ventilation or air-conditioning (instantaneous heat), while most of it is radiant heat. This is absorbed by walls, ceiling, floor and furniture (together with light, which is also converted to heat when absorbed). This heat is released to the indoor air later, possibly after the lighting has been turned off. Both forms of heat gains have to be considered in designing the building and its equipment.

Thus the total power of the lighting installation should be taken as internal heat gain.

For warm-humid climates the following recommendations can be made in connection with electric lighting:

- use lamps of the wattage appropriate for the room use
- replace, wherever possible, the incandescent lamps by fluorescent, considering their lower heat output and reduced electricity consumption.
- keep lamps turned off, unless lighting is required
- design spaces to use minimum artificial lighting during the day (rely on daylighting if possible)
- depending on activity or function of the room the placement of luminaires should match the areas of activity (e.g. workstations) i. e. use a lower level general lighting, supplemented by local lighting where required .

6 CONTROL HEAT GAINS FROM SURROUNDINGS

Inappropriately designed surroundings may adversely affect a building in urban zones, especially in warm climates. The environment may warm incoming air, thus resulting in a reduced performance of the bioclimatic techniques applied to the building and increase mechanical cooling requirements (and expenses).

To reduce thermal loads from the surroundings, exterior air temperature and heat gain from the earth surface should be controlled by different strategies which will be described here. It is possible to control the surroundings at two levels or scales: the site scale, which is the most frequent case for architects, and the urban scale, which is the concern of urban designers and town planners. The result will be the sum of contributions at all levels involved. In both scales, the same thermal factors are involved: solar radiation, heat generated by equipment, the long-wave radiant heat exchange, evaporative cooling, and air movement.

There are two types of objects that can modify the factors influencing the thermal balance, and thus affect the microclimatic conditions: artificial (constructed) and natural (vegetation) elements. These can be employed in trying to avoid overheating of the exterior: the ground surface and pavement around the building; which will also reduce the temperature of the surrounding air and lower the conductive heat flux from the ground to the interior of the building.

6.1 Use of built elements

6.1.1 Increase of ground surface reflectance

Solar radiation is the transfer of heat (and other wavelengths of energy) from the sun by electromagnetic waves, and it is the dominant element of microclimatic loads.
Albedo is the generalized diffuse reflectance of the ground and surrounding surfaces. It is the quotient of reflected radiation over incident radiation. For example: an albedo of 0.80 reflects 80% of the incident radiation. Light colours have a high reflectance (higher than 0.5), thus a reduced absorptance, resulting in lower surface temperatures, and consequently decreasing heat flow into the ground or the body. Light coloured building surfaces will also be at lower temperatures than dark ones.

It is useful to increase the albedo of city surfaces, using materials or surface finishes with a high reflectance, so that the surfaces absorb less heat and do not overheat. But reflected radiation should not fall upon vertical planes of other facades, as this would increase their thermal loads on these receiving surfaces.

6.1.2 Use of pavements with low thermal storage capacity

Pavements should not be thick in warm climates, and their thermal storage capacity should be low, to reduce energy storage and promote fast cooling down. This is generally difficult to achieve, since pavements are built with materials to withstand vehicular traffic, and are therefore dense and thick. However, paved areas should be reduced and should be combined with vegetation, to diminish the effects of construction materials and profit from the positive effects of vegetation.

6.1.3 Use of pavements with high long wave emittance

Radiation is absorbed by the surface of a body of material, which increases its temperature. Emittance (ε) is the ratio of radiation emission properties of a surface to that of a theoretical 'black body', the perfect emitter. Construction materials generally absorb short-wave (solar) radiation and emit long-wave radiation, but thermal balance with the surrounding is reached only at an elevated temperature.

It is useful to have surfaces with high emittance at long wavelengths, to facilitate cooling, especially at night time. In warm climates the combined effect of the material's reflectance and emittance must be considered.

White surfaces (lime whitewash, paint or white marble) show some selectivity: they may have an absorptance (α)the same as, or slightly greater than a polished metal (such as aluminium), but the white surface will remain cooler because of the high emittance of the white surface at terrestrial temperature (long wave) radiation. This effect is most pronounced for roof surfaces, facing the sky. (Hinz, et al 1986)

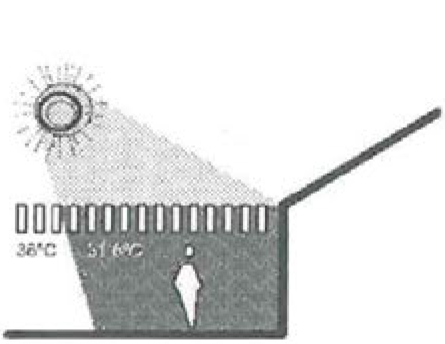


Fig. 6.1. Pergolas as solar protection

6.1.4 Use of built-in shade-generating elements

If a surface (e.g. a roof) is protected with a built-in element (such as a parasol roof) physical (optical and thermal) characteristics of the material must be considered.

The surface of this material should be reflective, and if not, appropriate air movement under it must be provided. If, for example, a thin material with high conductivity and high absorptance is used, the temperature of the space under this will be higher than the outdoor air temperature during most of the day. If however an insulating, or lightly coloured material is used, and abundant air movement is provided, temperatures no higher than that of the environment can be guaranteed.

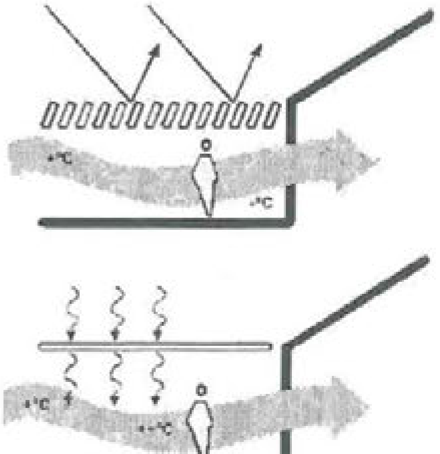


Fig. 6.2. Correct and incorrect use of elements as solar protection

6.1.5 Consider heat discharges to exterior air

Heat released by air conditioning condensers should be directed away from areas accessible by people. Heat released by sources outside the building should be minimised, but if this is outside the designer's control, such releases should be avoided. Air intake openings should avoid discharges by the building or by others.

6.2 Use of vegetation

According to Hinz et al. (1995) there are four major groups of vegetation: trees, shrubs, vines, and ground covers. Each has a specific function, but all control, in a greater or lesser degree, solar radiation through three processes: reflection, transmission, and absorption. A fourth process: evaporation is no less important.

Due to the darkness of its foliage, vegetation only reflects between 15 and 20% of the incident radiation, its absorptance is high and it is a total or partial shade generating element, and therefore can be used for solar protection.

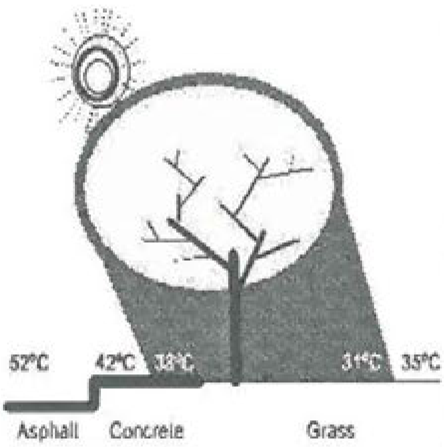


Fig. 6.3 Temperatures of the air and on the pavement under the shade of a tree

Vegetation absorbs solar radiation through photosynthesis and growing processes and this value varies from 0.6 to 0.9 (Refsnyder and Lull, 1965). This absorptance depends on the density of the foliage, location of the leaves on the tree, and leaf angle in relation to the sun. Most of this absorbed energy is converted into sensible heat, another part is re-radiated in long-wave form, especially at night and another part is dissipated by convection. The largest part of the absorbed (and not re-radiated) energy is consumed by evaporation and transpiration of the plant. A small part of this energy is stored by photochemical processes and by warming the plant and the ground (Hinz et al. 1996).

Foliage of a plant can substantially reduce short-wave radiation (thus providing shade) but transmit long-wave radiation, at a 5% rate, as the leaf structure is more transparent for the long wave parts of the spectrum (McPherson, 1984). This transmittance varies with the species.

Openings of buildings should allow comfort ventilation and appropriate replacement of warm air inside the building whenever required. There may be additional mechanisms inside the building to control convective exchanges. This process is most effective if the air intake is from areas kept cool by vegetation.

The different types of vegetation are discussed in the following paragraphs.

6.2.1 Trees

Trees have a height equal to or more than three meters. Trees have a capacity for the shading of large window surfaces roofs, and other built surfaces, depending on their different heights, crown spread, density of the foliage, branching, and leaf texture.

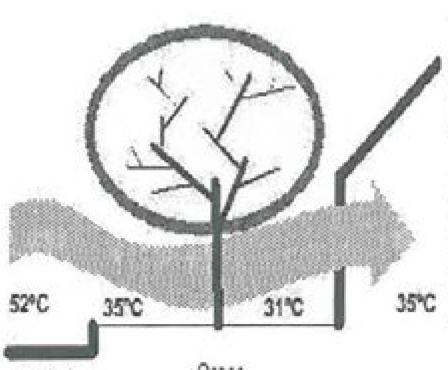


Fig. 6.4 Effect of trees on the envelope

Dense foliage allows reduction of a great percentage of solar radiation on the envelope (Hinz, 1995). Foliage is like a sky for the ground underneath, and its radiant temperature is higher than that of the sky, which causes a decrease of the infrared radiation emission of the surfaces under this foliage.

A tree is the best element to provide shade to a surface, because it controls solar radiation by reflection, absorption, and evaporation processes, and can consume or prevent great part of solar radiation reaching the shaded surface (Hinz, 1996). Air temperature under the shade of a tree will always be lower than the environment temperature. According to Parker (1971) the reduction of the ground temperature produced by the presence of a tree, under direct radiation, was 13.6 K, and under diffuse radiation this was 3.5 K. The effect of temperature reduction can also be observed on pavements.

6.2.2 Vines

Vines are climber plants, often supported by a trellis or a pergola. Their great advantage is that they can protect wide horizontal and vertical surfaces, creating shade faster and easier than a tree. The thicker the vines, the greater the resulting temperature reduction. Vines can also be used directly on walls, reducing the wall temperature by 1K below that of the exterior air, and 11K lower than that of a bare wall.

6.2.3 Shrubs

Shrubs are like small bushy trees, measuring up to about 1.5 m tall and 1.2 m wide. Shrubs can also decrease surrounding air temperature, but in on a smaller scale, because of their smaller spread and limited capacity to generate shade. Shrubs forming a hedge can be used to channel air movement, directing, accelerating, or reducing it, as desired.

6.2.4 Ground covers

This type of plants cover wide horizontal expanses with low height, between 100 and 400 mm. They do not prevent solar radiation falling on walls or windows of buildings. Ground covering is used to reduce paved surfaces, absorbing and dissipating heat, reducing the harmful effects of hard pavements. The temperature of a surface with ground covering can easily be up to 10 or 14 K lower than that of the exposed ground without vegetation. Ground covering reduces reflected radiation on walls, because its absorptance is around 0.8 and also reduces long wave radiation towards the walls from the immediate environment, and thus both long wave, and solar heat gain are reduced.

If mechanical cooling is used, and air ('sink') temperature near the condenser of the air conditioner is lowered, the CoP of the system will improve, and the machine will consume less energy for a same amount of cooling.

Ground covering can also be used as a passive cooling system for the air, decreasing air temperature before it comes in contact with the building.

Table 6.1 shows the influence of various landscaping elements in reduction of wall temperatures and Table 6.2. shows annual costs for cooling of houses built with concrete blocks. These tables can serve as reference to see the influence of adequate landscaping on the thermal behaviour of the building and its energy based 'active' control systems.

Table 6.1 Reduction of temperatures in light coloured walls with an east west orientation and shaded by landscaped elements

landscape elements	reduction under beam radiation	reduction under diffuse radiation
trees	3.5 K	13.6 K
shrubs	4.2 K	13.5 K
trees + shrubs	5.5 K	15.5 K
ground cover 1	4.4 K	7.6 K
ground cover 2	5.6 K	8.8 K

(Parker, 1971)

Table 6.2 Annual costs for cooling in houses

	foliage type	annual cooling cost ($)
unshaded reference prototype		1134
walls shaded	light (33%)	1064
	dense (67%)	993
roof shaded	light (33%)	1106
	dense (67%)	1070
	total (100%)	1039
roof + walls shaded	light	1032
	dense	932
unshaded:		
colour of roof and walls	dark	1240
	light	1079
general comparison	'hard' landscape	1240
	'soft' landscape	898

(Buffington, 1971)

It has been shown in this chapter that a bioclimatic landscaping can be used to effectively reduce the thermal impact on buildings through adequate design of exterior spaces, increasing the efficiency of cooling systems and 'passive' techniques used in the building.

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INDEX

PLEA Notes published so far:

1. *Solar geometry* by S V Szokolay
2. *Thermal insulation* by A Zöld & S V Szokolay
3. *Thermal comfort* by A Auliciems & S V Szokolay
4. *Daylighting* by A Majoros
5. *Climate analysis* by M Docherty & S V Szokolay