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Title: A simplified method for the calculation of the influence of the room mass on the indoor thermal climate in buildings under summer conditions.

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S U M M A R Y

Simplified methods and design aids for the calculation of cooling loads and room air temperatures are described. The complicated influence of the room mass is approximated by introducing the 'thermal effective mass' of the room. This quantity accounts for the restricted penetration of the fluctuating radiative heat loads into the walls - considered from room side - and is defined in such a way that a linear relation with the cooling load is obtained. The purpose of the work is to provide the designer with handsome means to be used in the first stages of a building design when only rough building data are available.

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1. Introduction

The accurate calculation of room temperatures and cooling demands in office buildings under varying outside and indoor conditions requires a complicated calculation model. However, since the introduction of computers, it has become very well possible to do these calculations for design purposes as well. The programmes are based on calculation models which schematically describe the heat conduction in the walls, the radiation between the walls and the convection at the wall surfaces for varying outdoor temperatures, solar radiation and internal heat sources. Several mathematical methods are followed such as 'finite differences', 'finite elements', 'response factors'.

The advancing technology and expertise in mainframe computers and computer models leads to programmes with more possibilities e.g. better simulation of convection transfer in roomzones and air cavities - but at the same time requiring more extensive input data. However, most of these extensive data are only available in the advanced stage of building design. This explains the demand for more simplified means by which it is possible to try out alternative design variants in the early stages of the design when only basic building data are available: dimensions, type of constructions, fenestration etc.

Such methods and means are described here.

An essential simplification is the introduction of the 'specific effective room mass'.

2. The thermal effective mass of a wall

When the surface of a wall is exposed to a fluctuating radiative load (solar radiation, radiation from lighting), the outer parts of the wall (seen from room-side) will accumulate more heat than the inner parts on account of the limited penetration depth of the temperature wave. This means that the cooling load contribution of a radiative heat source increases non-linearly with the thickness (mass and heat capacity) of the wall.

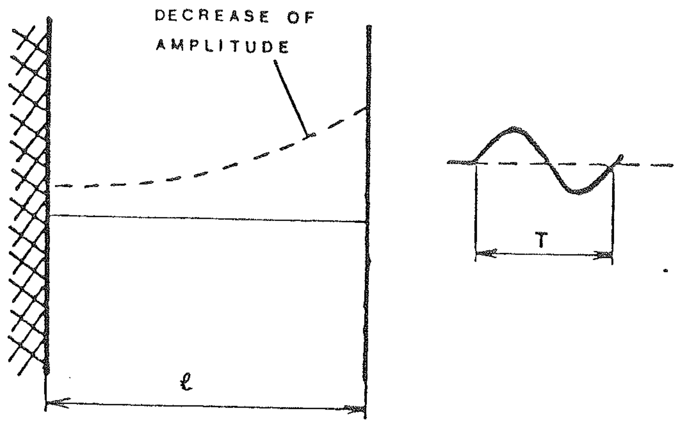


Figure 1: The damping of a sinusoidal temperature wave in a homogeneous wall, fully insulated at the back side.

If the wall should be substituted by an infinitely conducting (fictive) wall with the same ρc and with such a thickness that the cooling load will be unchanged, then the relation between the cooling load contributions and the mass (or heat capacity) of the substitution wall should be linear.

Such an equivalent thickness is introduced here and is called the thermal effective thickness d_e of a wall. Likewise the product ρd_e is called the specific thermal effective mass of the (homogeneous) wall. And the product $\rho c d_e$ the specific thermal effective heat capacity of the wall.

The linear relation between the cooling load given off by a heat irradiated wall and the thermal effective mass (or heat capacity) of that wall is the main principle of the methods under consideration here.

It is to be noted that the specific heat c of rocky materials in buildings - only these materials are of interest here - shows only relatively small differences.

An indication for the value of d_e can be derived from the analytical solutions for the damping of sinusoidal temperature waves in walls [1]. For a homogeneous wall, thickness l and fully insulated at one side (fig. 1), the decrease of the amplitude is smaller than about 2% when

$$l < 0.5\sqrt{\frac{\lambda T}{\Pi \rho c}} \qquad (1)$$

where: λ is the thermal conductivity of the material, ρc the volumetric heat capacity and T the periodic time of the sinusoidal fluctuation.

For the ususal rocky materials and T = 24 h, the value of l is as follows:

	$\frac{\lambda}{\rho c}$ (m^2/s)	l (cm)
brick	$0.45.10^{-6}$	5.1
limestone	$0.60.10^{-6}$	6.4
concrete	$0.90.10^{-6}$	7.9

Overall mean value about 6.5 cm

Walls of these materials and respective thicknesses accumulate uniformly and are fully "thermally effective".

Generally actual constructions have other thicknesses. To find practical (possibly mean) values of d_e for rocky and concrete walls, calculations for real situations were carried out. For these calculations an available cooling load programme is used, described in [2], and fitted for this purpose.

In case of a partition wall (identical conditions on both sides), in figure 2 the boundary conditions are given for both the real wall A and for the substitution wall B. The latter has $\lambda = \infty$, but the same ρc as the real wall A. The thickness d(B) was varied in order to find the situation in which Q_c (B) = Q_c (A). This procedure, graphically explained in figure 3, was carried out for both a solar radiation load (south) and for a lighting radiation load (during office hours). The results are given in table 1.

Table 1: Values of the thermal effective thickness d_e for some rocky materials.

Material		d_e (cm)	
λ W/(m.K)	ρc J/(m^3.K)	solar radiation (south, July)	lighting radiation
0.45	$1.1 \cdot 10^6$	8.0	7.0
0.70	$1.4 \cdot 10^6$	8.4	7.2
1.9	$2.0 \cdot 10^6$	10.5	8.0

Overall mean value: about 8 cm.

3. Insulating surface layer

Insulating layers like carpets, sound absorbing material on ceilings, etc., reduce the thermal effective mass.

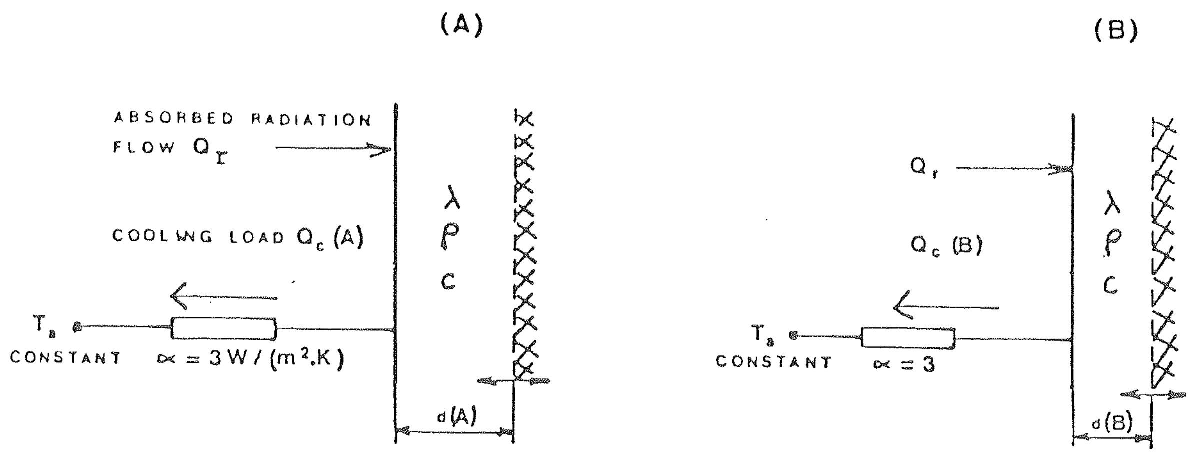


Figure 2: Boundary conditions for the determination of the thermal effective thickness d_e in case of a partition wall.

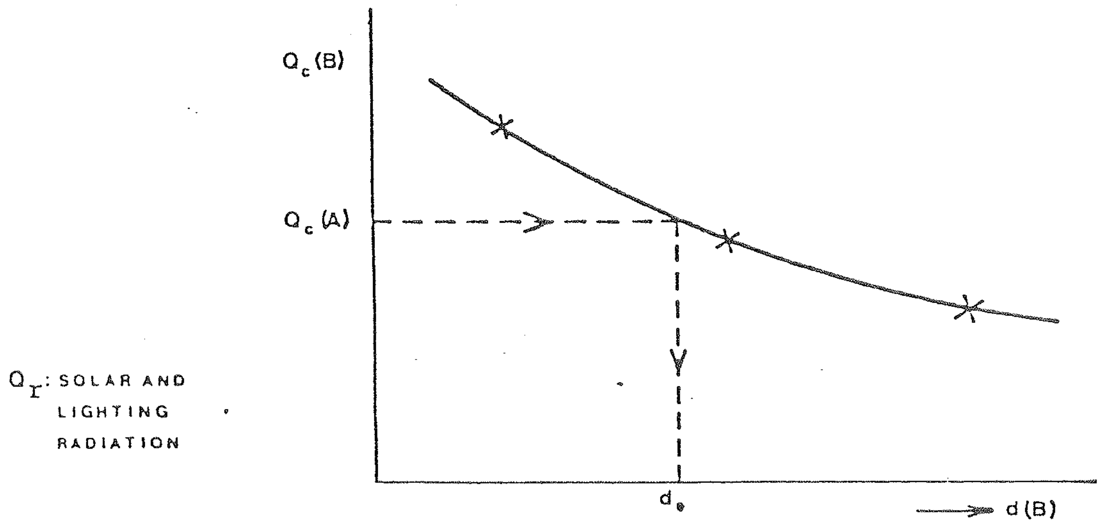


Figure 3: Determination of d_e under the condition:
$Q_c(B) = Q_c(A)$.
Type of solar radiation load, south, July.
Lighting radiation: block-shaped.
Calculation base:
Solar radiation: $Q_c(A)$ and $Q_c(B)$ at 14.00 hours.
Lighting radiation: $Q_c(A)$ and $Q_c(B)$ average values during office time.

To account for this effect a reduction factor f is introduced defined by:

$$f = \frac{Q_c \text{ without cover}}{Q_c \text{ with cover}} \qquad (2)$$

The factor f is time dependent. For various constructions and situations the value of f is determined by calculating the cooling load contribution Q_C with and without an insulating surface layer.

In the case of solar radiation the value of f occurring at the moment of maximum radiation is a real mean value for the period 2 to 3 hours before and after the moment of maximum load.

In the case of (block-shaped) lighting radiation the average value of f during the lighting-on period appears to be quite comparable with the average value of f for solar radiation as mentioned above.

In table 2 these values of f are given for three kinds of rocky materials.

Table 2: Average values for the reduction factor f.

material	f
bricks with λ = 0.45	0.85
bricks with λ = 0.7	0.73
concrete with λ = 1.9	0.60

5. The specific effective mass of a room (SEM)

Similar to the thermal effective thickness d_e and the reduction factor f as described in par. 2 and 3, it is possible to formulate a thermal effective mass of a room defined by:

$$SEM = \frac{\Sigma \bar{f} \cdot m_w}{A_r} \qquad (3)$$

where: SEM is the specific thermal effective mass of the room in kg/m^2,
m_w is the effective mass of the wall, roof etc. in kg

$$m_w = \rho_w \cdot \bar{d}_e \cdot A_w$$

with ρ_w is the volumetric mass of the material; $\bar{d}_e$ is the mean thermal effective thickness as described below in m;
A_w is the surface area of the wall, roof, etc.;
$\bar{f}$ is the mean reduction factor for insulating layers (as described below);
$A_r = \Sigma A_w$ is the total inside surface of the room, in m^2.

In the methods and means to be described in par. 5, the quantity SEM is the linearized room mass parameter. Regarding the values for d_e and f, mentioned in par. 2 and 3, as indications, for many room situations (different walls, different heat loads), the maximum cooling demand (from both the radiative and the convective parts of athe solar and lighting loads) is calculated as a function of SEM. The values $\bar{d}$ and $\bar{f}$ were varied in such a way that a linear relation between the maximum cooling load and SEM was obtained.
This resulted in the following rules for the determination of SEM in practical situations.

Concerning $\bar{d}_e$

- In case of partition walls and floors it is to be supposed that the heat loads in the adjacent rooms are identical. So the mass of these constructions, assuming symmetrical composition, does not contribute to the accumulation of the room for no more than the middle of the construction. So the value of $\bar{d}_e$ is no larger than half the total wall or floor thickness.

- In case of rocky inner walls and partition floors, and in case of massive rocky outer walls, roofs and groundfloors, a thickness of at the most 6 cm (including plaster, if any) is taken into account - apart from an insulting layer (if present) or cover for which the factor $\bar{f}$ is introduced.

- In case of composite outer walls and roofs only the inner part of the construction up to any insulation layer, and in case of rocky material at the most 6 cm (including plaster, if present) is taken into account - apart from a possible insulating layer or cover on the room-side.

- Parts of vertical walls, which are masked by the lowered ceiling or a hightened floor are not taken into account, that is: neither in the mass m_W nor in the internal surface A_W.

Concerning $\bar{f}$:
In case of insulating layers like carpets, wood panels, sound absorbing (and thermal insulating) materials with normal thickness , lowered ceilings, for $\bar{f}$ a value of 0.7 can be taken. Plasters are considered to be non-insulating ($\bar{f}$ = 1).
By means of a handsomely tabulated calculation scheme the value of SEM can easily be determined.

5. Applications

The specific effective mass SEM is used in the methods for global indoor climate calculations as will be described in this paragraph. Only the essentials are given.

5.1. Influence of room mass on the cooling load

For global design purposes a simplified cooling load method is developed, in which the cooling load parts caused by solar and lighting radiation absorbed at the inner wall surfaces, are calculated by the following linear relations.

a. Radiation part of lighting heat. The cooling load is calculated by introducing the heat storage factor s_l:

$$s_l = s_l(0) + \left[s_l(100) - s_l(0) \right] \cdot \frac{SEM}{100} \qquad (4)$$

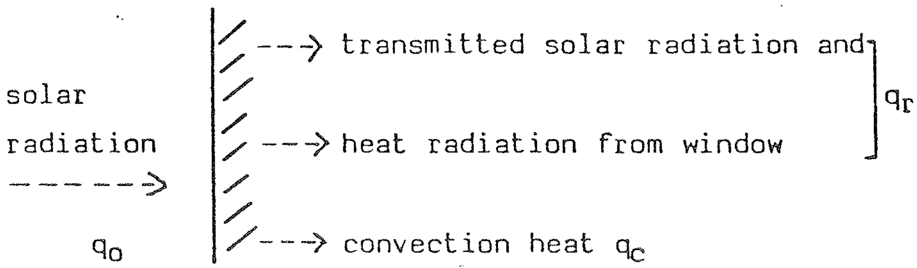
where: $s_1(0)$ is the heat storage factor for the radiation part of the lighting when SEM = 0 kg/m^2 and $s_1(100)$ is the same factor when SEM = 100 kg/m^2.

The values for $s_1(0)$ en $s_1(100)$ are tabulated for each hour of the day and for each operation hour of the lighting or part of the lighting.

b. <u>Solar radiation transmitted through windows and absorbed at indoor wall surfaces.</u> The cooling load is calculated by introducing the specific solar radiation cooling load q_{sg}, implicitly defined by:

$$Q_{sg} = STF.A_g.z\left[q_{sg}(0) + \{q_{sg}(100) - q_{sg}(0)\}\frac{SEM}{100}\right], \text{ in } [W] \quad (5)$$

Q_{sg} is the cooling load caused by solar radiation transmitted through a window, in W;
A_g is the area of the glass panes, in m^2;
STF is the solar heat transmission factor, defined by



q_r and q_c caused by solar radiation only, not by overall heat transmission outside/inside

$$STF = \frac{q_r + q_c}{q_o} \quad (6)$$

z is a reduction factor for shadowed parts of the window;

$q_{sg}(100)$ is the cooling load caused by solar radiative heat load (through windows) per m² glass area and STF = 1, when SEM = 100 kg/m²;

$q_{sg}(0)$, the same when SEM = 0 kg/m²

The hourly values $q_{sg}(0)$ and $q_{sg}(100)$ are tabulated for each summer month, nine window orientations separately for window systems with and without indoor sunshading device.

5.2. Influence of room mass on room temperature

When the hourly cooling load of a room (at constant room air temperature) is known, the increase of the room air temperature in case of no cooling can be calculated by

$$\Delta T_{r,t} = \sum_{n=1}^{24} Q_n \cdot TR_n \cdot A_r^{-1} \text{, in [K]} \qquad (7)$$

where $\Delta T_{r,t}$ is the increase of the room air temperature on timepoint t of the 'temperature calculation day' (5th day), when cooling is stopped after the 'cooling load calculation day';

Q_n is the cooling load at constant room air temperature on timepoint n of the 'cooling load calculation day' (5th day from start), in W;

TR_n is the response of the room air temperature caused by a heat source of 1 W at time n of the 'cooling load calculation day' and at the same time n of the following days, in K/m² room surface area;

A_r is the area of the total internal surface of the room enveloping constructions, in m².

To correct for the changes in transmission and infiltration heat transfer caused by the temperature increase $\Delta T_{r,t}$, the parameter K is introduced:

$$K = (\bar{U}.\ A_o + \rho.c.\dot{V})/A_r,\ \text{in } W/(m^2.K) \qquad (8)$$

where: $\bar{U}$ is the mean U-value of the outer walls, in $W/(m^2.K)$;

A_o is the total surface area of the outer walls, in m^2;

ρc is the volumetric heat capacity of the air, in $J/(m^3.K)$;

$\dot{V}$ is the free ventilation air quantity, in m^3/s.

The values of the temperature response factor TR_n are tabulated for each hour n (of the cooling load calculation day) and for:

- main time points t of the temperature calculation day,
- $K = 0, 4, 8, 12, 16\ W/(m^2.K)$,
- $SEM = 0\ kg/m^2$ and $SEM = 100\ kg/m^2$.

So, in this case two interpolations have to be carried out: one for the actual value of K (linear by approximation) and one for the actual value of SEM (linear by definition). To simplify the calculation, a handsome scheme is made for practical use.

A complete description of these cooling load and room temperature calculation methods is given in [5]. For both calculations a computer programme has been developed for use on a micro computer.

5.3. Design aids for the determination of acceptable window size and required sunshading in buildings without mechanical cooling. Parameter SEM

For office buildings without mechanical cooling, design aids are developed to determine the maximum window sizes and the required sunshading in order to prevent too high indoor air temperatures. This in relation to the main building properties and circumstances such as: building mass, orientation, window partly movable or not, internal heat load.

The design aids are presented in the form of graphs in which the spectific effective mass is parameter. Examples are given in figures 4 and 5. Here window size and solar transmittance are expressed by the quantities PG and STF:

PG is the percentage of glass in the façade, based on indoor sizes

STF is the solar heat transmittance factor.

Other parameters are:

- acceptable temperature level TMAX in relation to air velocity conditions.
- type of glazing and sunshading
- orientation : based on south and south-west (only office hours)

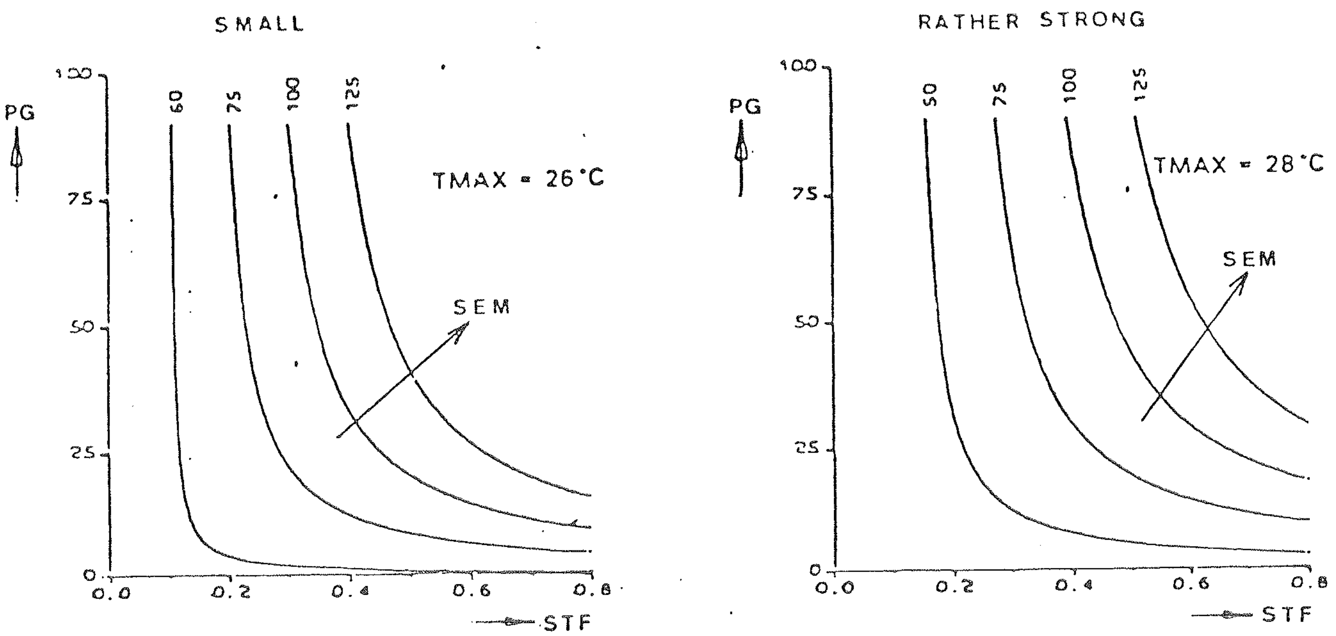
  for south-east: maximum STF-value 1.2 x

  for east : maximum STF-value 1.4 x

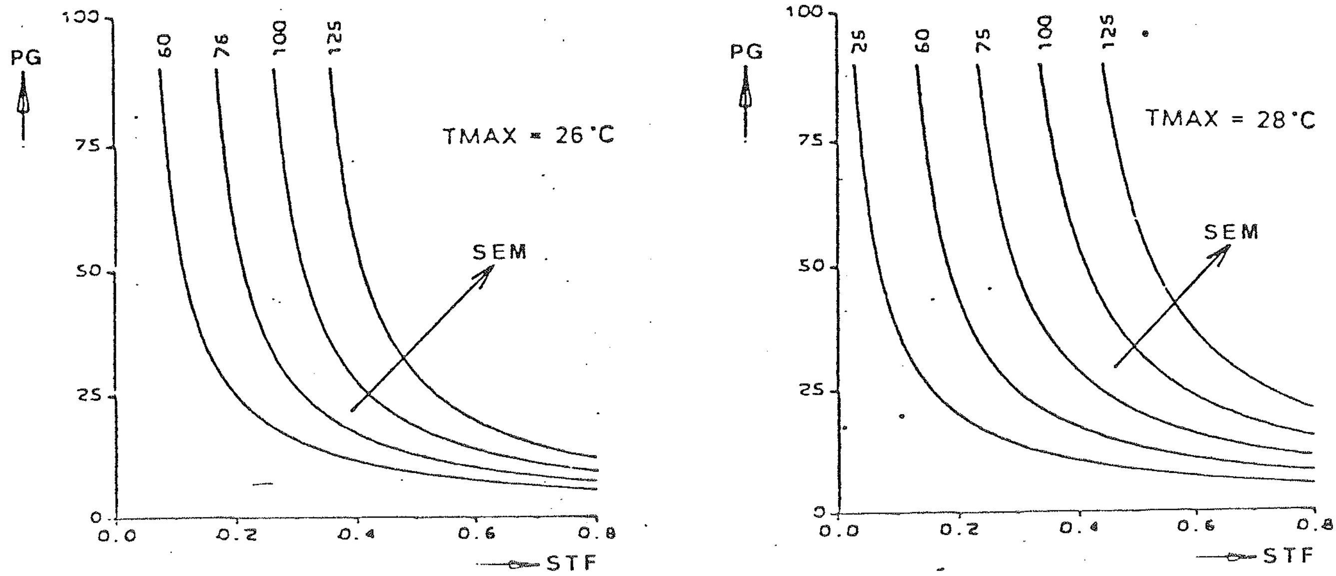
Similar graphs are made for other types of glazing.

The graphs are valid for a mean climatic year in the Netherlands.

The work is published in [6].



single glass without inside shading



single glass with inside shading

Figure 4: The maximum acceptable STF-value as a function of the percentage glass PG, or the maximum percentage of glass PG as a function of STF, for south and west (only office time).
Other variables:
specific effective mass SEM
air movement conditions
other orientations: south-east: maximum STF 1.2 x
east : maximum STF 1.4 x
ventilation: 3 airchanges per hour during office time
internal heat load: 10 W/m^2 floor area (on sunny days)
outdoor conditions: mean climatic year in The Netherlands.

Glazing and sunshading: single glass.

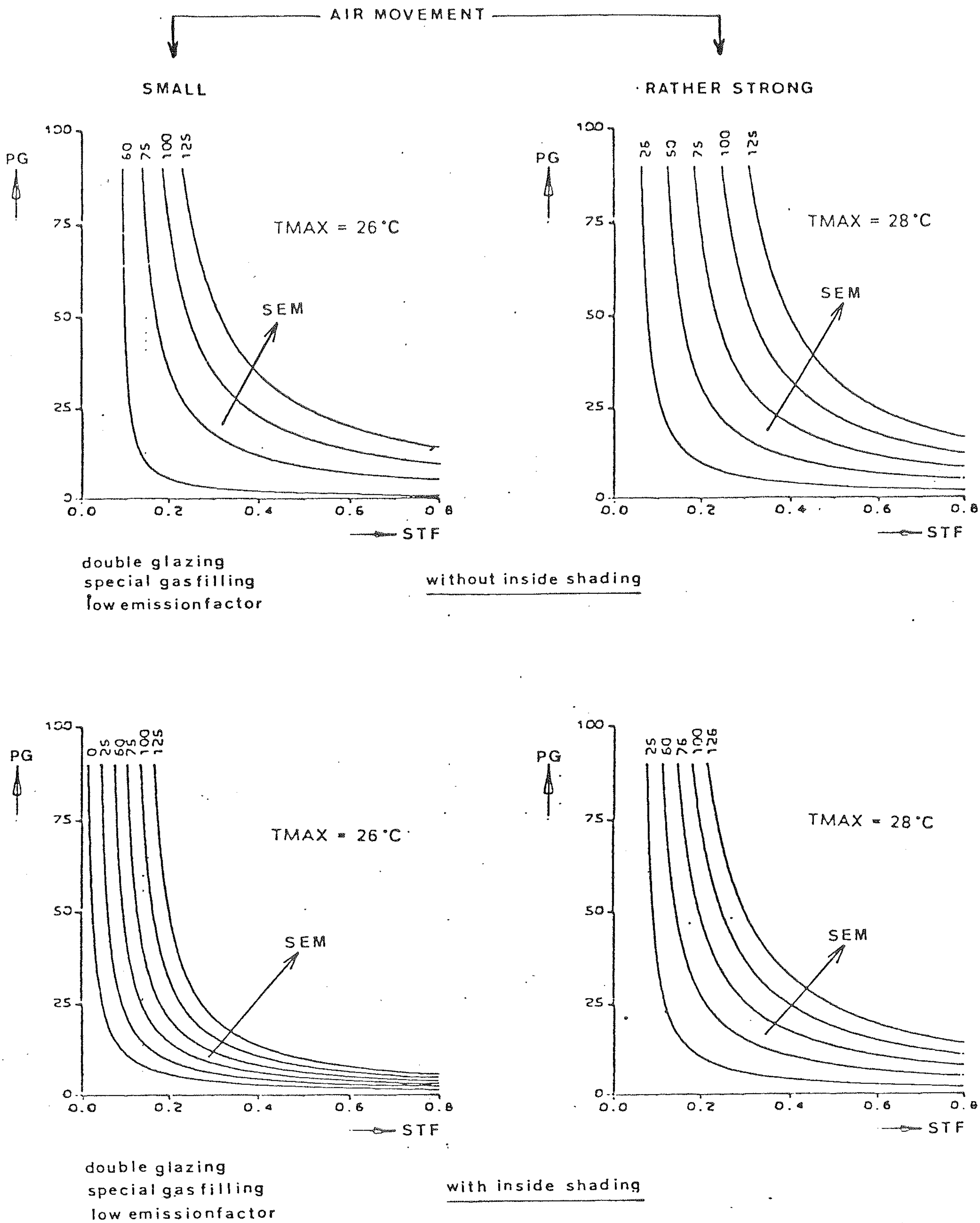


Figure 5: As in figure 4, but:

Glazing and sunshading: double glazing
special gasfilling
low emission factor

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