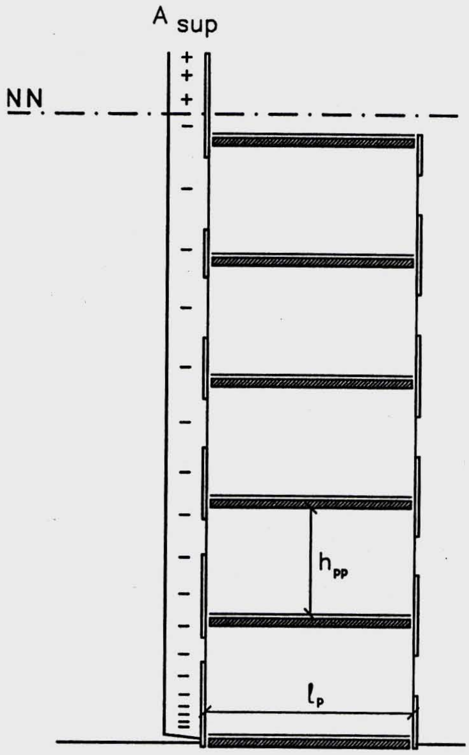
ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Double-Skin Walls



INSTITUT DE TECHNIQUE DU BATIMENT DEPARTEMENT D'ARCHITECTURE - 1998

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List of symbols

a	Light absorption coefficient	-
A	Total effective cross section	m^2/m_{lin}
A_H	Upper canal geometric aperture	m^2/m_{lin}
A_B	Lower canal geometric aperture	m^2/m_{lin}
A_{sup}	Effective upper canal aperture section	m^2/m_{lin}
A_{inf}	Effective lower canal aperture section	m^2/m_{lin}
$C_{d,H}$	Discharge coefficient upper aperture	-
$C_{d,B}$	Discharge coefficient lower aperture	-
D_G	Air flow rate	$m^3/h.m_{lin}$
g	Gravity acceleration	m/s^2
G	Solar intensity on facade	$W/m.m_{lin}$
G_{air}	Intensity transmitted to the air	$W/m.m_{lin}$
H	Total double-skin canal height	m
$h_{étage}$	Floor height	m
h_{pp}	Distance between floor and ceiling	m
h_t	Distance from neutral zone level to the top of the canal	m
I	Intensity (of radiation)	W/m^2
l_p	Room depth	m
m	Meteorological variable, $m = I/\Delta T$	W/m^2K
n	Air change rate	1/h
N	Number of floor levels, max. number of floors that can be ventilated	-
N^*	$N^* = N - h_t / 2 . h_{étage}$	-
T_B	(absolute) Temperature of the air at the canal base	K
T_H	(absolute) Temperature at the top of the canal	K
T_{en}	(absolute) Temperature at the canal entrance	K
T_{canal}	(absolute) Temperature in the canal	K
U	Thermal transmittance	W/m^2K
$v_{B,}$	Air velocity at lower aperture	m/s
v_H	Air velocity at upper aperture	m/s
α	Heat transfer coefficient	W/m^2K
α_{ext}	Heat transfer coefficient with outdoor air	W/m^2K
α_{int}	Heat transfer coefficient with indoor air	W/m^2K
ΔT	Temperature difference	K
$\rho . C_p$	Thermal volume capacity of air	J/m^3K

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Foreword

The present report summarises research work done under the heading 'Incidence of the Typology of Double-Skin Walls on their Energy Performance and Building Physics Behaviour' (Incidence de la typlogie des facades double-peau sur leurs performances énergétiques et en physique du bâtiment).

It is under this title that a proposal accepted in 1993 by the Swiss Federal Office of Energy allowed us to pursue experimental and theoretical research work.

The first step was to gather information about double-skin walls constructed in Europe as well as world-wide in order to build up a classification and extract the main typologies.

In the following steps we performed laboratory measurements and simultaneously built up a computer-based mathematical model. Laboratory measurements (as well as on-site measurements carried out in Geneva by Pahud [1]) allowed the validation of the mathematical model, which was then further used in parametric studies.

Finally, reports regarding daylighting and acoustic problems were established under the direction of Professor J.-L. Scartezzini (LESO-PB) and M. Rossi (LEMA).

The final report, which presents the complete work carried out in the framework of this project is structured as follows.

The first volume (Chapters 1 to 4) gives a brief description of the physical bases of double-skin systems and the main properties of these systems, with some practical hints. This volume is principally aimed at architects and engineers who are planning to construct a double-skin facade with the best possible chances of success.

The second volume (Chapter 5) reports all on-site and laboratory measurements. It will be of interest foremost to physicists and building engineers but also to architects who will find the analysis of two practical cases that are very different in their architectural expression and physical behaviour.

The third volume (Chapters 6 to 9) explains the physical principles and their mathematical developments, on which the practical conclusions summed-up in the first volume are based. The parametric studies, on which numerous practical rules are based, are also reported in this volume. And finally, it contains the general conclusions.

The fourth and fifth volume (Chapter no. 10) contain all the supporting files established for the purpose of the project. There you will find the typology study completed and updated, the in-situ measurement files (Telecom-PTT and Felimob buildings) as well as the daylighting and acoustics reports.

1. Introduction

Numerous double-skin facades are currently being built or planned on new buildings as well as on existing buildings. Correctly designed, the double-skin facade ('facade double-peau' in French and 'Doppelwandfassade' in German) presents interesting features: thermal insulation, summer overheating protection, thermal and visual comfort as well as acoustic insulation. Its correct planning nevertheless requires architectural and constructive mastery of a great number of elements and factors, whose interactions are not easily mastered (Table 1.1).

The present project[1] studied the influence of various architectural and constructive parameters and showed their mutual interactions, in order to establish guidelines that would lead architects and engineers toward optimal technical solutions compatible with architectural requirements.

Element or factor of influence	Thermal balance		Thermal comfort		Daylighting Visual comfort	Noise Acoustic comfort	Natural room ventilation
	Cold season	Hot season	Cold season	Hot season			
Kind of screen glazing (external skin)	-	-	-	-	X X	X	-
Kind of facade glazing (internal skin)	X X	X X	X X	X X	X X	X	-
Screen-facade gap	X	X X	X	X X	X	X	X
Double-skin canal height	X	X X	X	X X	-	-	X X
Facade glazed fraction (internal skin)	X	X X	X	X X	XX	X	-
Shading systems	X	X X	X	X X	X X	-	-
Double-skin canal ventilation	X	X X	X	X X	-	X	X X

Table 1.1 : Influence of various elements and factors on the performance of a double-skin facade. It is to be observed that the influences are generally greater during the hot season than during the cold season.

[1] The present work takes its origins from papers by M.J. Holmes [2], [3] and [4].

2. Typology

From the outside to the inside, a double-skin facade is made of (Fig. 2.1):

- a glazed screen (external)
- a space delimiting the canal
- the facade (internal)

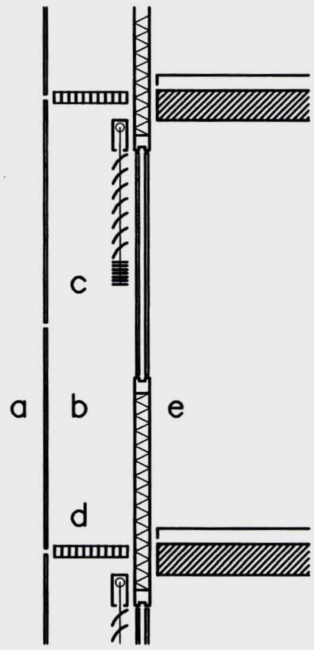


Figure 2.1 : Double-skin facade
a screen
b canal
c solar protection
d duck board
e internal facade

The *screen* is generally made of a single pane of glass, without framing.

The *canal* is 50 to 600 mm wide. It spans at least one floor, but most often 3 floors or more.

The *shading systems* are generally located in the canal, close to the screen or close to the facade. When the canal is wide enough, a duck board allows cleaning and maintenance of the fixed and mobile parts.

The *internal facade* is fully glazed; sometimes there is an opaque breast wall.

An inventory of already constructed or planned double-skin facades allowed defining the following typologies.

2.1 Cross-section typology

The various types result on one hand from the facade structure (solar protection, breast wall, Fig. 2.2) and on the other hand on the ventilation scheme of the double-skin and the adjoining rooms (Fig. 2.2).

Most of the time, the shading system is located in the double-skin canal and the internal facade has no breast wall [5].

When the double-skin wall canal is split up by the floor slab, the rooms are ventilated floor by floor through the double-skin [6] (Figure 2.3, case a). When the canal extends over more than one story, room ventilation is possible through the double-skin (air in and out, case b) or cross-ventilation (air in through the building, out to the canal, case c).

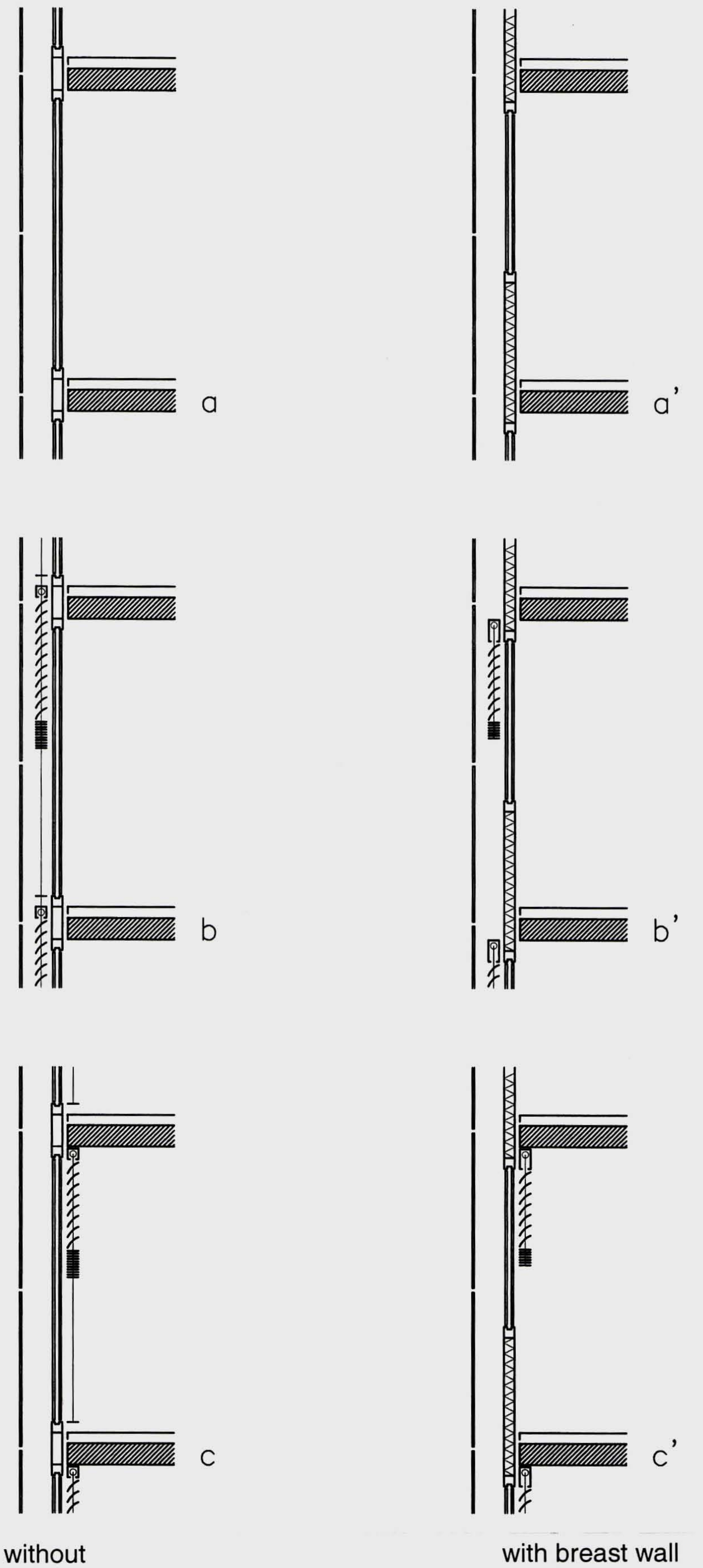


Figure 2.2 : Double-skin facade - Cross section typology

a, a' without any shading system (very unfavourable)

b, b' shading system inside the double-skin canal

c, c' shading system inside the room (with prejudice to hot season comfort)

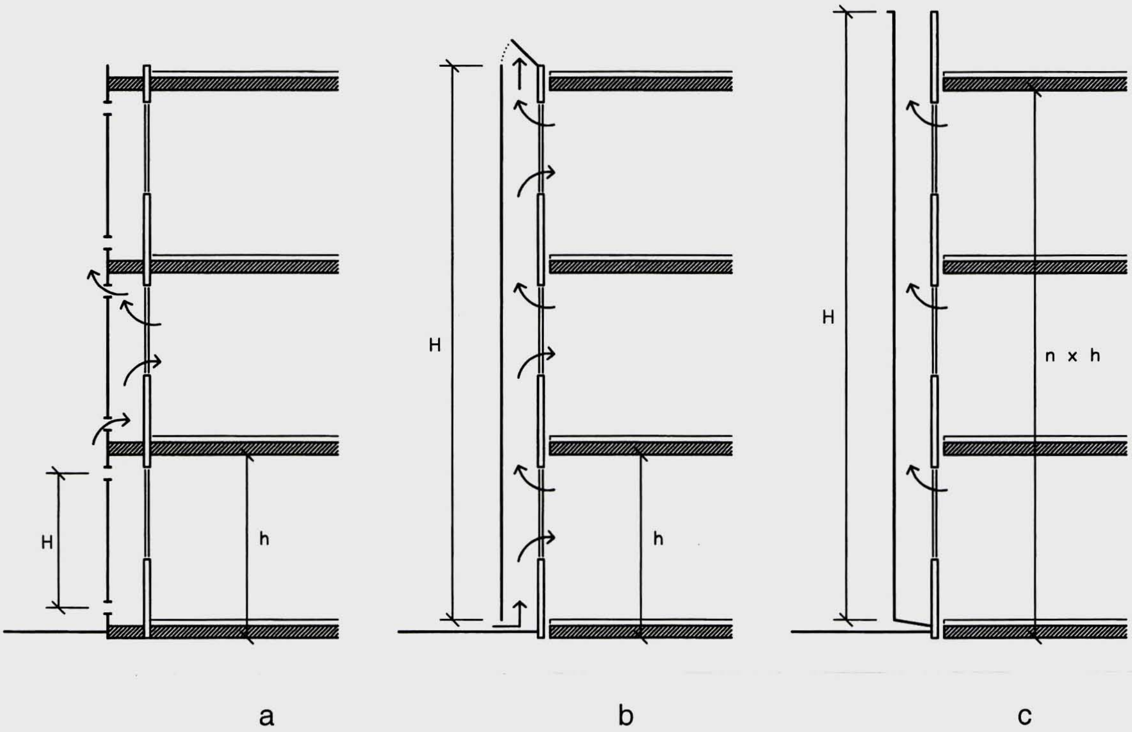


Figure 2.3 : Double-skin wall canal - Cross section typology

a) H < h the canal is split up by the floor slab

b) H > h the canal extends over more than one floor

c) H > n . h the canal extends above the last floor

2.2 Longitudinal Section Typology

The choice of a particular longitudinal section typology is closely related to the ventilation strategy of the double-skin canal and the adjoining rooms.

When the stack effect is limited to a single floor height, there is always a risk that the hot air that leaves one floor goes into the "fresh air" inlet of the next floor. This danger can be reduced through a vertical separation of the inlets and outlets (Fig. 2.4 a) or through a *diagonal* ventilation scheme with out of line inlets and outlets (Fig. 2.4b). In both cases the rooms can be ventilated by opening the windows to the canal of the double-skin wall.

The ventilation of the double-skin canal is strongly enhanced when its height extends over several levels. In the simplest execution (Fig. 2.5a), a valve in the upper position allows the canal to be shut in the cold season. When the sun is shining, the air warms up gradually and the ventilation of the rooms through the canal varies strongly from one floor to the other. In order to avoid this defect, but nevertheless benefit from the total stack effect height at each floor (Fig. 2.5b), one can separate the fresh air inlet from the used air outlet through a diagonal ventilation scheme on each floor. In planning a cross ventilation of the rooms together with a heightened canal (closed at ground level), it is also possible to guarantee equivalent comfort level conditions at all floors (Fig. 2.5 c).

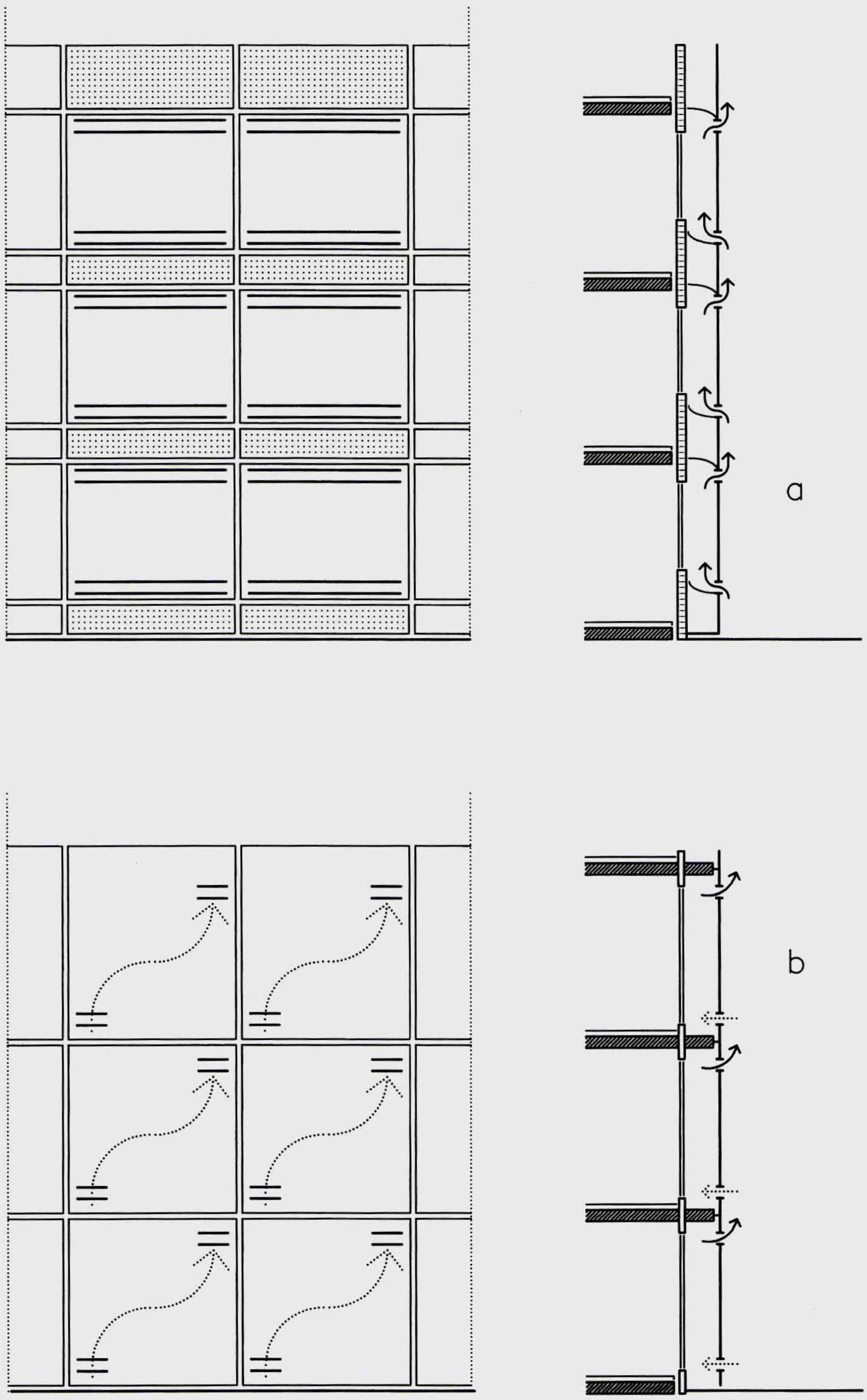


Figure 2.4 : Longitudinal section typology

Floor by floor ventilation of the double-skin

a) When the fresh air inlet at one floor is far enough from the air outlet of the next floor, air inlets and outlet may be superposed one above the other.

b) By separating air inlets and outlets through a diagonal scheme, a shortcut between them is avoided.

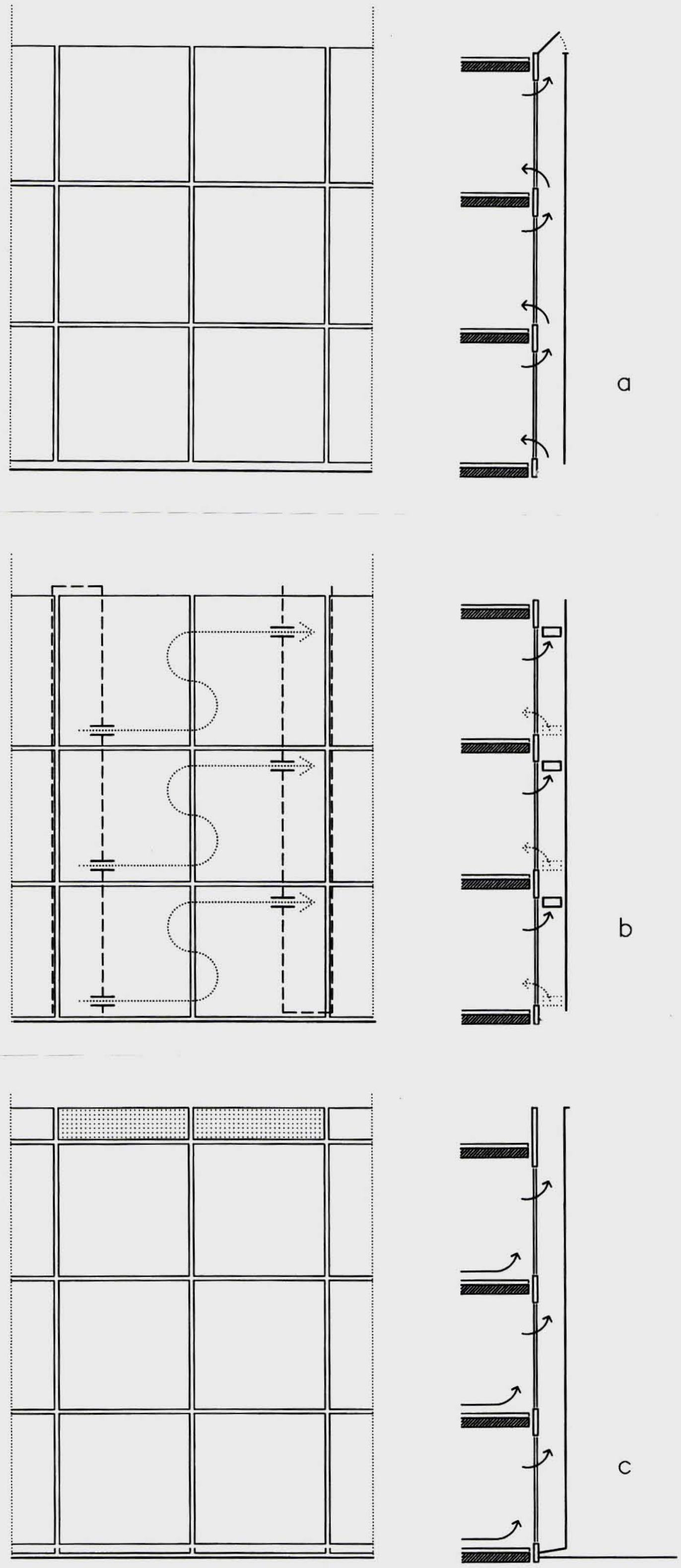


Figure 2.5 : Longitudinal section typology. Double-skin ventilation over several floors.

a) In the simplest execution scheme, a valve closes the canal at its top (during the cold season). The air temperature in the canal rises floor by floor.
b) In order to allow equivalent temperature condition at all levels, fresh air is taken in the left hand canal (open at its base) and polluted air goes out through the right hand canal (closed at its base).
c) Rooms are cross ventilated. The double-skin canal stack effect is mainly due to the warming of the air in the upper part of the canal that rises above the roof level.

3. Working principle

The working principle of any double-skin facade is always the same: the stack effect. A column of hot air (of low density) is surrounded by cooler air (obviously at higher density). The resulting stack effect (in French "poussée d'Archidème") makes the air move. Let us first consider the simplest case: all the windows to the canal of the double-skin are kept closed [3].

3.1 *Double-skin against air-tight facade*

The double-skin facade defines a canal of width d, height H and inlet A_{inf} and outlet A_{sup} sections, generally given in square meters per linear meter of facade. The air enters the canal basis at temperature T_B and leaves after warming up (through the facade itself or through solar gains) at temperature T_H.

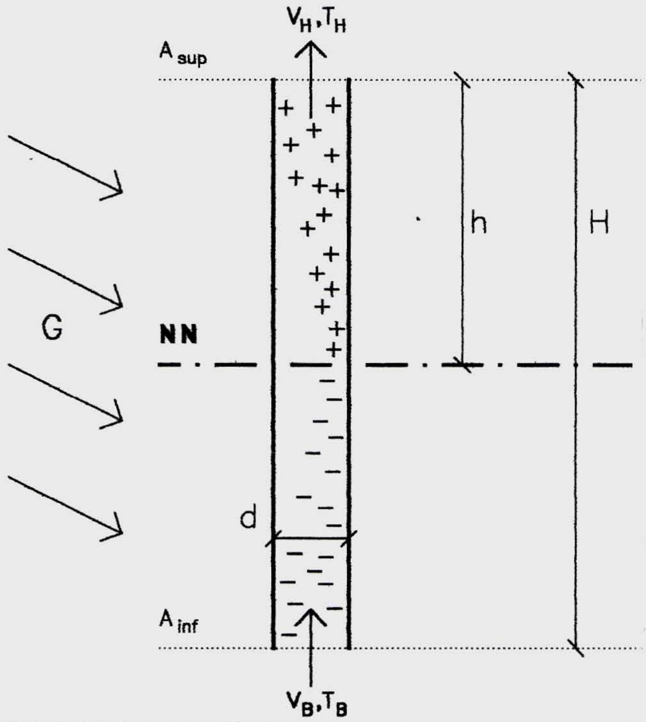


Figure 3.1.1 : Working principle
- - - low pressure zone
+ + + high pressure zone
NN neutral zone

A low pressure zone builds up at the canal basis and a high pressure zone is observed in the upper section (Fig. 3.1.1). There is consequently at distance h_t from the top of the canal a zone called "neutral zone" where the pressure inside the canal is exactly equal to the outdoor pressure [7]. Assuming that the air movement in the canal is bound to the energy conservation law (Bernoulli Law) and that mass flow is conserved through the lower A_B and A_H openings, one can calculate the distance h_t of the neutral zone to the top of the canal [8].

A detailed discussion of equations 1 to 12 is to be found in Chapter 6 Physical Principles.

$$h_t = \frac{H}{1 + (T_B / T_H)(\frac{A_{\sup}}{A_{\inf}})^2} \tag{1}$$

T_B	(absolute) temperature at the canal basis
T_H	(absolute) temperature at the canal top
A_{sup}	$= C_{d,H} \cdot A_H$; $A_{inf} = C_{d,B} \cdot A_B$
	where A_H and A_B are the geometric apertures and $C_{d,H}$ and $C_{d,B}$ the corresponding discharge coefficients
h_t	distance from the neutral zone to the top of the canal..

The upper part of the canal is a high pressure zone, the zone under the neutral zone a low pressure zone. In choosing $A_{sup} < A_{inf}$, the neutral zone is lowered, giving rise to a large high pressure zone; in choosing $A_{sup} > A_{inf}$ the neutral zone rises, making room for a large low pressure zone.

The air flow through the double-skin canal takes away the heat that warms up the air according to the law

$$\Delta T^3 = (\frac{G_{air}.H}{\rho\, c_p})^2 \frac{T_B}{g.H} \frac{1}{A^2} \tag{2}$$

G_{air} . H	total power given to the air (per linear facade length)	($P_{air} = G_{air}$. H)	[W/m_{lin}]
ρ. c_p	thermal volume capacity of air		~1200 [J/m^3K]
g	gravity acceleration		9.81 [m/s^2]
H	canal height		[m]
A	total effective cross section such as		[m^2]

$$\frac{1}{A^2} = \frac{1}{A_{\sup}^2} + \frac{1}{A_{\inf}^2}$$

According to this equation, the air temperature rise is only weakly bound to the power transmitted to the air (see Table 3.1.2, ΔT prop. to $(P_{air})^{2/3}$).

The air flow rate through the apertures is given by

$$D = \frac{3600}{\rho\, c_p} \frac{G_{air} H}{\Delta T} \cong 3 \frac{G_{air} H}{\Delta T} = 3 \frac{P_{air}}{\Delta T} \quad [\mathrm{m^3/hm_{lin}}] \tag{3}$$

To obtain the discharge velocity, the air flow rate is divided by the corresponding aperture geometric section:

$$v_H = D/A_H \quad ; v_B = D/A_B \qquad (4)$$

The example given below shows that when the power transmitted to the air is multiplied by eight, the air temperature rise is only multiplied by four and the air speed by two.

G_{air} [W/m . m_{lin}]	P_{air} [W/m_{lin}]	ΔT [K]	D [m^3/h . m_{lin}]	V_{Base} [m/s]	ΔT / P_{air} [K/kW]
50	500	2,2	682	0,76	4,4
100	1000	3,5	857	0,95	3,5
200	2000	5,5	1091	1,2	2,8
400	4000	8,8	1364	1,5	2,2

Table 3.1.2 : Double-skin against air-tight facade.
Air flow rate, speed and temperature rise as a function of power transmitted to the air (H = 10 m, T_B = 300 K, A_{sup}/A_{inf} = 0,5/ 0,25 m^2/m_{lin}).

3.2 Room ventilation through the double-skin canal

As seen before (equation (1)) the neutral zone position is primarily related to the relative dimensions of the lower and upper apertures of the canal. If these are equal, the neutral zones lie at mid-height of the canal. Through a small hole in the facade under the neutral zone level, the air will leak from the building to the canal. The reverse effect will be observed above the neutral zone level. Pressurising the building above or under the outdoor pressure, would change this situation in one or the other direction.

Considering the typology illustrated in Figure 2.5, one sees that under schemes 2.5a and 2.5b rooms have to be kept airtight against the rest of the building (doors closed): except at neutral zone level, there is always underpressure (lower levels) or overpressure (upper levels) compared to the outdoor pressure. Opening the doors to the corridor would alter the air movements in the room and possibly in the double-skin canal.

3.2.1 *Room ventilation provided by the double-skin facade*

To be able to use the stack effect in the double-skin to provide the ventilation of the rooms (extraction mode), many conditions have to be fulfilled [9]:

- in order to have all the levels situated in the underpressure zone of the canal, it is necessary that the neutral zone level is located above the aperture (in the facade) of the upper level,
- the upper aperture of the double-skin canal ($A_{sup} = A_h \cdot C_{d,H}$) has to be large enough to be able to evacuate the air extracted form the various levels,
- finally, it is necessary, in order to get an equal air change rate at the different levels, to balance the air circuit between them and to minimise the interactions between floors as far as air movements are concerned.

Let us consider an N level building with one facade opening to the outer space and the other in the canal of a double-skin. One seeks to ventilate the rooms with an air change rate n by using the double-skin stack effect as the "motor" of natural ventilation.

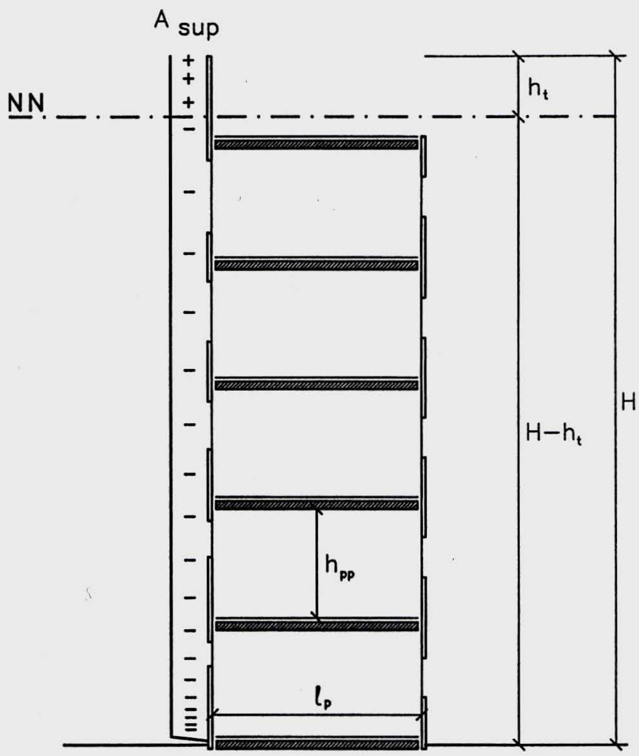


Figure 3.2.1 : Double-skin providing natural room ventilation

The dimensional characteristics are the following:

H	Overall double-skin height	[m]
h_t	Distance from neutral zone level to the top of the canal	[m]
N	Number of floors	
h_{pp}	Floor to ceiling height	[m]
l_p	Room deepness	[m]
n	Air change rate (fresh air)	[1/h]
A_H	Upper canal geometric aperture (per linear length)	[m^2/m_{lin}]
D	Air flow rate	[$m^3/s \cdot m_{lin}$]
$\overline{V}_H$	Mean air velocity in the upper aperture	[m/s]

Shaded facade

In urban surroundings, it is possible that only the upper part (of height h_t) is sunlit. In that case, the ventilation "engine" is limited to the power transmitted to the air on height h_t :

$$P_{air} = G_{air} \,.\, h_t \qquad [W/m_{lin}] \qquad (5)$$

To ventilate all the rooms with the desired (fresh) air change rate n, the overall air flow rate is

$$D = \frac{n}{3600}(N.\,l_p\,.\,h_{pp}) \qquad [m^3/s] \qquad (6)$$

In order to evacuate this air flow rate through the double-skin facade, the upper aperture section A_{sup} has to be wide enough, that is

$$A_{\sup} \geq D^{3/2}\,\frac{1}{h_t}\sqrt{\frac{\rho\, c_p\,.\,T_{entrée}}{g\,.\,G_{air}}} \qquad [m^2/m_{lin}] \qquad (7)$$

(with $A_{sup} = A_H \,.\, c_d$ and $g = 9{,}81\ m/s^2$)

$T_{entrée}$ is the (absolute) temperature of the air leaving the rooms.

If by contrast the upper aperture section is imposed, then there is a limit to the number of floors N that can be ventilated.

$$N \leq \frac{3600}{n.l_p\,.h_{pp}}(A_{\sup}\,.h_t)^{2/3}\,(\frac{g\,.G_{air}}{\rho\, c_p\,.T_{entrée}})^{1/3} \qquad (8)$$

Equations (7) and (8) may be given in graphic form or easily computed on a spread sheet. The air temperature rise (in the upper part of the canal) may be computed in the following way:

$$\Delta T = \frac{P_{air}}{\rho\; c_p \cdot D}$$

$$\Delta T \cong 3\frac{P_{air}}{n\,(N.l_p\,.h_{pp})} \qquad [K] \qquad (9)$$

Again a graphic representation can be given or the data can be computed on a spread sheet. An example of a shaded building ventilated through the double-skin facade with a required air change rate of 6 is given in Table 3.2.2 (summer situation).

G_{air} [$W/m^2\ m_{lin}$]	$N \leq$	N_{max}	H [m]	$\Delta T \geq$ [K]	P_{air} [W/m_{lin}]	$P/\Delta T$ [$W/K\ .\ m_{lin}$]
100	3.76	3	11.9	1.5	200	133
200	4.74	4	15.2	2.3	400	178
300	5.42	5	18.5	2.7	600	222
400	5.97	6	21.8	3.0	800	267

Table 3.2.2 : Shaded building ventilated though the canal of a double-skin wall.
Sunlit height $h_t = 2$ m, Air change rate $n = 6\ h^{-1}$
Floor height $h_{pp} = 2{,}8$, depth $l_p = 8$ m
Effective upper aperture $A_{sup} = 0{,}6\ .\ 0{,}84 = 0{,}5\ m^2/m_{lin}$
The table above indicates the maximum number of floors, the overall height of the double-skin canal as well as the air temperature rise. It may be noticed (last column) that the rate of thermal power transmitted to the exhaust air to its temperature rise increases with the transmitted power.

Unshaded facade

In open space, the whole facade may be unshaded, which implies that a radiation intensity G_{air} is uniformly transmitted to the air over the total height of the double-skin canal. The equations shown previously are still valid if one takes into account that

$$P_{air} = G_{air}\,(h_t + N\ .\ h_{étage}) = G_{air}\ .\ H \tag{10}$$

The number of ventilated floors is now given by

$$N \leq \left(\frac{3600}{n.l_p.h_{pp}}\right)^{3/2} (A_{sup}.h_t)\sqrt{\frac{G_{air}.g.h_{étage}}{\rho c_p.T_{en}.h_t}} + \frac{1}{2}\frac{h_t}{h_{étage}} \tag{11}$$

and the air temperature rise

$$\Delta T \geq 3\,\frac{G_{air}.H}{n\,(N.l_p.h_{pp})} \tag{12}$$

Considering again the building taken as an example in the preceding paragraph (Table 3.2.2) but assuming that this time it is fully unshaded (Tables 3.2.3 and 3.2.4), it may be noticed that the number of naturally ventilated floors through the double-skin canal is greatly enhanced. A possible limitation is now to be related to the admissible air temperature rise.

G_{air} [W/m^2]	N ≤	N_{max}	H [m]	ΔT ≥ [K]	P_{air} [W/m_{lin}]	P/ΔT [W/K . m_{lin}]
100	9.9	9	31.7	8	3170	403
200	13.8	13	44.9	15	8980	582
300	16.9	16	45.8	23	16440	717
400	19.4	18	61.4	31	24560	806

Table 3.2.3 : Building ventilated through the double-skin canal. No shading.
Floor height : 3,3 m. Other data as for shaded building.
The number of floors that can effectively be naturally ventilated through the double-skin is greatly limited by the air temperature rise. The thermal power transmitted to the air lies between one quarter and half the incident solar power.

G_{air} [W/m^2]	N ≤	N_{max}	H [m]	ΔT ≥ [K]	P_{air} [W/m_{lin}]	P/ΔT [W/K . m_{lin}]
100	12,8	12	42.9	8	4290	538
200	17.9	17	59.4	16	11880	762
300	21.8	21	72.6	23	21780	941
400	25.1	24	82.5	31	33000	1075

Table 3.2.4 : Building ventilated through the double-skin canal. No shading.
Same data as the preceding table but h_t = 3.3 m.
The improvement of the system is to be noticed; its origin is in the greater distance h_t between the neutral zone and the summit of the canal.

3.2.2 A thermodynamic model of the double-skin facade.

The double-skin facade is a thermal engine that works on the inside and outside of the canal temperature difference. Writing again equation (8) in a different way

$$(8) \qquad \frac{n.N.l_p.h_{pp}}{3600} \leq (A_{\sup}.h_t)^{2/3} \left(\frac{g.G_{air}}{\rho c_p.T_{entrée}}\right)^{1/3}$$

one has on the left hand side the air flow rate that the double-skin facade can extract from the building, whereas on the right hand side, the product ($A_{sup}.h_t$) which represents the solar heated air volume is multiplied by (g . G_{air} / ρ c_p . $T_{entrée}$) in which one finds the solar intensity transmitted to the heated air. The significance of equation (8) is then the following:

$$\begin{pmatrix} \textit{ventilation capacity} \\ \textit{of double-skin wall} \end{pmatrix} \sim \begin{pmatrix} \textit{volume of} \\ \textit{heated air} \end{pmatrix} * (\textit{heating power})$$

or in a more familiar way

(mechanical work) ~ (engine capacity) * (gaz pedal)

3.3 Thermal Balance

Night time operation (no solar radiation) has to be clearly distinguished form daytime operation.

3.3.1 Night-time operation (no solar radiation)

The external skin (as a rule warmer than the outdoor air) looses energy through radiation as well as conduction and convection. The screen (external glazed facade) limits the radiation losses to the clear sky (see 4.1 or 4.3). Convection losses occur mainly with the air rising in the double-skin canal, air that "licks" the external wall in its ascendant movement and carries off almost half the energy. The thermal protection due to the screen is enhanced where the *thermal insulation of the internal skin* is improved.

3.3.2 Daytime operation

Solar radiation (direct and diffuse) is partly absorbed by the glazing (screen and internal facade), by the structure and the solar blinds located in the double-skin canal (when these are lowered). The result is firstly a greenhouse effect that makes the room temperature rise and secondly the warming up of the air inside the double-skin canal, which generates the chimney effect. Both effects are profitable in the cold season. They may, however, be disturbing in the hot season, especially on west oriented facades.

4. Properties and Practical Recommendations

Chapter 3 gave a short presentation of the main principles governing the operation of a double-skin facade. The theoretical justification of these principles is summarised in two papers [4] and [5] and presented in some detail in Chapter 6.

The present chapter is dedicated to the particular properties of different types of double-skin walls and to the practical recommendations attached to these. The proposed conclusions are based on one hand on experimental observations reported in Chapter 5 and on the other hand on a series of parametric studies performed with the mathematical model TQV presented in Chapter 5. These studies are discussed in Chapter 8 Parametrical Studies.

Two types of facades are considered: double-skin against airtight facade (4.1) and double-skin that provides natural room ventilation (4.3).

To get the best clarity and user-friendliness, the presentation of these two types is completely independent, at the cost of some repetitions. The main differences between them are summarised below:

Double-skin against airtight facade	Double-skin that provides natural room ventilation
• The choice of the canal width is not critical.	• The canal depth has to be determined precisely.
• The canal is open at the bottom and may be closed (by a valve) at the top.	• The canal, closed at its base, extends above the last floor level.
• Normally, the windows are closed. Opening the windows does not guarantee good room ventilation.	• Ventilation of the rooms is obtained by opening appropriate valves (sized floor by floor).
• The double-skin has virtually no noise-insulating effect.	• Noise insulation can be improved by the presence of the screen of the double-skin.
• Owing to the air temperature rise in the canal (with sun radiation), the canal height is limited to 3 to 4 levels.	• The allowed height depends on the canal sizing. An upper limit is nevertheless given by the allowed air temperature rise in the canal (10 to 15 levels...).

4.1 Double-Skin against Airtight Facade

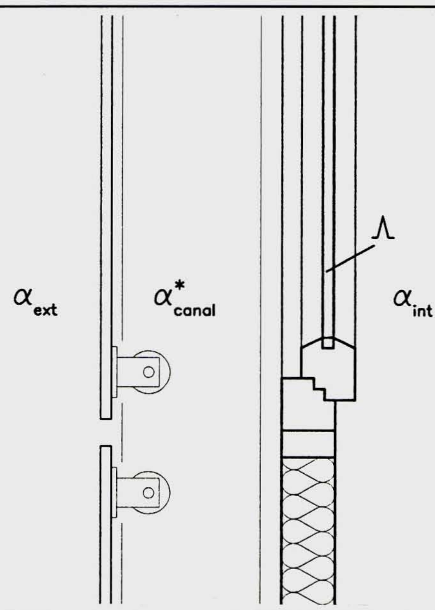
Although the performance of this type of facade is not the most interesting, it is often chosen because of its simplicity.

- ***Night-time thermal insulation - U value computation***
  The inner facade thermal insulation is enhanced by the presence of the screen. The air movements inside the double-skin canal nevertheless limit the gains to be expected and this even if the air movements are limited by closing the valves at the top aperture. In order to take into account the air leaks of these valves, two cases have been considered:

$$A_{sup} / A_{inf} = 1$$

$$A_{sup} / A_{inf} = 1/10$$

The U value of the double-skin facade can be computed in the usual way if one takes the data given in Table 4.1.1 for the thermal heat transfer coefficient of the canal. These only weakly depend on the canal height or discharge coefficient C_d.



$$\frac{1}{k} = \frac{1}{\alpha_{ext}} + \frac{1}{\alpha^*_{canal}} + \frac{1}{\Lambda} + \frac{1}{\alpha_{int}}$$

Glazing type	A_{sup}/ A_{inf}	Canal depth	
		0,6 m	0,2 m
V_1	1/1	15	13
	1/10	10	8
V_3	1/1	13	12
	1/10	9	7

α^*_{canal} [W/m²K] values as a function of glazing type (of inner facade) and top to bottom aperture ratio.

V_1 Double-glazing 4/12/4 $\Lambda_1 = 6{,}5$ [W/m²K]

V_3 Triple glazing with low E layer : 4K/12/4 K/12/4 $\Lambda_3 = 1{,}6$ [W/m²K]

Depending on the canal height and discharge coefficient, α^*_{canal} data given above is to be adjusted as follows:

Height	< 10 m	raise α^*_{canal} by 1 W/m²K	
	> 30 m	lower α^*_{canal} by 1 W/m²K	
Discharge coefficient		$c_d \leq 0{,}25$	lower by 1 W/m²K
		$c_d \geq 0{,}35$	raise by 1 W/m²K

Table 4.1.1 : Equivalent heat transfer coefficient α^*_{canal} of the double-skin canal.

- ***Clear Sky Radiation***
  As shown by Th. Franck [10], the building heat loss to the clear sky gives rise to supplementary heat losses with an intensity that is independent of the outdoor or building temperatures.

The practical rules are the following (see 7 Establishing the Practical Rules).

U value computation

- The value is computed in the usual way and gives the thermal heat transmission factor (per unit area) from the inside to the environment and outdoor air (see preceding §).

Supplementary heat losses to the clear sky

- Vertical surface radiation to the clear sky gives rise to supplementary heat losses ΔR of about 25 [W/m^2] for a partly overcast sky. Large discrepancies around this mean value are observed starting at 0 (heavily overcast sky) and rising to 60 [w/m^2] (clear sky, dry air).
  These values have to be nearly doubled for a horizontal surface.

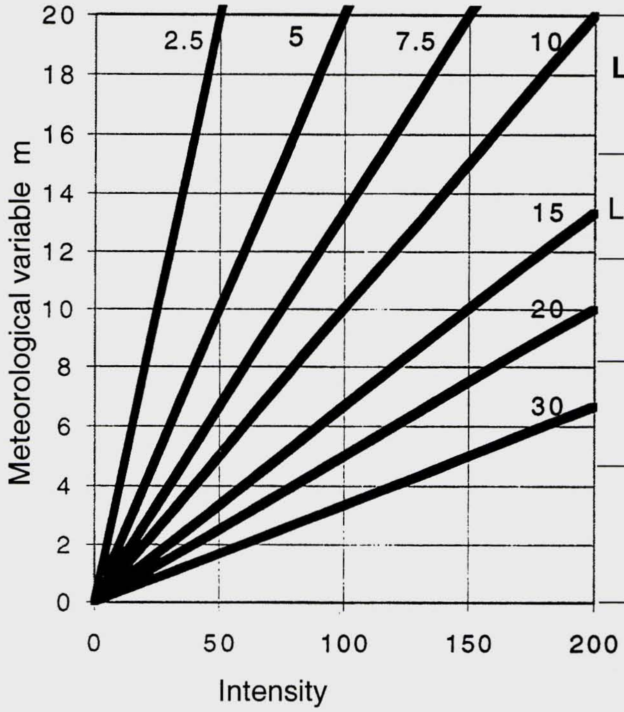
- Heat losses to the clear sky are partly drawn from the facade itself and partly from the outdoor air (through heat exchange with the outdoor air)

- The *relative* rise of the facade heat losses (relative U value change) only depends on the temperature difference $\Delta T = T_{indoor} - T_{outdoor}$. It accounts for 8% in the case of a 20 [K] temperature difference without any reference to the particular wall U value.

- The *absolute* rise of the facade thermal losses [W/m^{2}k] is by contrast proportional to the U value and to ΔR. If U = 1 [W/m^{2}k] and ΔR = 25 [W/m^{2}k], then one expects a 1.64 [W/m^{2}k] supplementary heat loss and this without any reference to the indoor to outdoor temperature difference.

- ***Behaviour in the cold season – Thermal comfort***
  The insulation quality offered by a double-skin facade depends foremost on the insulation quality of the *inner wall.* It is therefore recommendable to equip the internal wall with high-performance glazing mounted on a highly insulated breast-wall and framing. This is the only condition for the double-skin facade to perform better than an equivalent simple facade (i.e. with the *same total number* of glazed surfaces with the same selective layers).

  If there is no breast-wall, there are considerable solar gains. Added to the internal gains (occupants, machines and lighting), they suffice to compensate the losses (by conduction through the facade and by ventilation) as soon as the meteorological variable m (Table 4.1.2) exceeds 3,5 [W/m^{2}K] (with artificial lighting) or 5 [W/m^{2}K] (without artificial lighting). For larger m values, a solar shading system is necessary (Table 4.1.3). A detailed justification of these data is presented in Chapter 8, Parametric Studies.



Location	Nov. Dec. Jan.	Feb. March	October or April
Lausanne	4,5	5,5	11,5
Zürich	4	6,5	10,5
Sion	4,8	7,5	13,2
Davos	4,8	6,3	9

Meteorological variable m

Table 4.1.2 : The meteorological variable $m = I / \Delta T$ [$W/m^2 K$]
The heat balance of a system with solar gains can be related to the meteorological variable m (left table); the table on the right gives some mean monthly values :
cold season $4 < m < 6$; mid-season $\cong 10$; summer > 10 [$W/m^2 K$]
$\Delta T = T_{indoor} - T_{outdoor}$ [K]

m [W/m^2K]	**Facade global heat balance**
< 2	Negligible solar gains.
3,5	Cold season, sun low on the horizon. Solar and internal gains (occupants, services and artificial lighting) probably compensate for heat losses.
5	Cold season, clear sun. Solar and internal gains (occupants and services) make up for the heat losses.
> 6	Shading system mandatory.

Table 4.1.3 : Double-skin facade operation during the cold season.

- ***Summer shading – summer comfort***
  Compared to a conventional facade, the double-skin facade is more likely to experience overheating and should consequently be fitted with an effective shading system that is located in the double-skin canal and well ventilated through the air circulating in the double-wall canal. There is no advantage in using the screen as a permanent solar protection: reflecting or absorbing, it only imperfectly reduces unwanted solar gains but hampers the desired daylight and reduces the daylighting autonomy.

  A blind (canvas or slats) reduces the heat gains by a factor 3 to 5 depending on the outdoor temperature and radiation: the greatest efficiency is observed when the outdoor temperature is lower than the room temperature and solar radiation is limited.

  For all solar radiation in excess of 100 W/m^2, the surface temperature of the indoor glazing is higher than the room air temperature. The effect of the blind is to lower this temperature by 1 or 2°C (and to cut direct radiation).

  The dynamic (time dependent) behaviour of the room - and thus the comfort experienced in clear hot weather - is strongly related to the room ventilation scheme and its thermal inertia. There is a clear benefit in restricting the solar gains by reducing the (internal wall) glazed area and in delaying the heat gains through the opaque parts by prolonging the thermal time delay of the breast wall.

- ***Room ventilation***
  With strong solar radiation, ventilating the rooms to the double-wall canal becomes problematic: the upper floors receive the hot air from the lower floors.

  If the double-wall runs over many floor levels, cross ventilation is possible for the floors situated under the neutral zone.

- ***Condensation risk***
  A well insulated internal facade fitted with high-performance glazing and framing does not show any condensation risk on its indoor surface.

  By contrast, in cold weather with a clear sky, there is a condensation risk on the outdoor surface of the internal facade as well as on the screen. This annoyance common to highly insulated building envelopes generally vanishes in the morning.

4.2 Recommendations : Double-skin against airtight facade

☐ **Screen**

The screen should be made of clear glazing, without (or with a minimum of) framing. Reflections from absorbing glazing do not provide enough protection from the sun but they limit the daylighting autonomy. They are to be avoided (see Daylighting).

Extending the screen height above the last floor level (roof) allows the extension of the canal (see hereafter, double-skin canal). Movable openings located in the screen surface deteriorate the stack effect in the canal and do not improve room ventilation.

Significant acoustic protection is possible only if the screen is airtight (no slit, no opening) (see Acoustic aspects).

☐ **Internal facade (main facade)**

High thermal performance glazing (U < 1,6 W/m^{2}K) with high daylight transparency is worthwhile in winter as well as in summer. It is mounted on airtight frames with a thermal resistance that matches the U value of the glazing. Thermal comfort is enhanced by a correctly chosen glazed fraction. The choice should be dictated in priority by the daylighting needs (see Daylighting). The breast wall thermal resistance should be high (U < 0,5 W/m^{2}K) with a thermal delay of about 8 hours.
Depending on the screen and canal design, the required acoustic insulation will have to be provided by the internal facade alone (see Acoustic aspects).

☐ **Double-skin canal**

The operation mode of the double-skin facade and the glazing cleaning scheme are to be taken into account when choosing the canal depth. A depth of between 20 and 60 cm has no influence on the air movements in the canal.

A possible duck board, fixings and obstructions located in the canal slow down the air movement and reduce the equivalent aperture of the air stream. This aperture can be computed as follows:

$$\frac{1}{A_{tot}^2} = \frac{1}{A_{\text{sup}}^2} + \frac{1}{A_{\text{inf}}^2} + \sum_j \frac{1}{A_j^2}$$

where A_j makes reference to the various obstructions located in the double-skin canal.

The presence of a duck board influences the amount of daylight available in the room (see Daylighting).

The overall height of this type of double-skin wall is limited to 3 to 4 floor levels (in order to limit the temperature difference between the top and the bottom of the canal).
Valves located at the top of the canal allow a reduction of the air movements during the cold season.
Extending the canal height over the last floor and choosing correctly the A_{sup} to A_{inf} ratio enables equivalent ventilation conditions at all levels (see 4.3).
The screen acoustic protection may be strongly reduced by the presence of the bottom aperture (see Acoustic aspects).

☐ **Shading systems**

Effective shading systems (canvas or slat) are mandatory. For practical (and esthetical) reasons they are located inside the double-skin canal. They are placed at a certain distance from the facade in order to favour air circulation.

Acoustic aspects

Well planned, a double-skin facade improves protection against outdoor noise. This effect may also be noticeable when the windows are open. Nevertheless, depending on the way the screen is implemented, there may be no additional outdoor noise reduction at all.

Forecasting the acoustic noise reduction of a double-skin facade is a complex matter because many parameters have to be taken into account. It is wrong to think that the overall noise reduction of the facade is obtained by adding the noise reduction of the screen to the noise reduction of the main wall.

For this reason, it is risky to plan reduced noise reduction values for the main facade without consulting an acoustics engineer.

In order to improve the outdoor noise reduction performance of a double-skin facade, the following rules have to be followed:

- Plan an airtight screen, i.e. there should be no direct sound propagation path from outdoors to the canal: openings, slits between elements, etc. are phonic bridges.
- The screen should be made of a sufficiently heavy and/or thick material in order to obtain as high as possible a mass per unit area - typically over 15 kg/m^2; nevertheless, if the thickness exceeds 5 mm, a stratified structure is preferable.
- Choose a canal depth between the airtight screen and the main facade of between 20 and 50 cm.
- In order to avoid that vibrations propagate through the iron work from the screen to the main facade, supple joints should be used.
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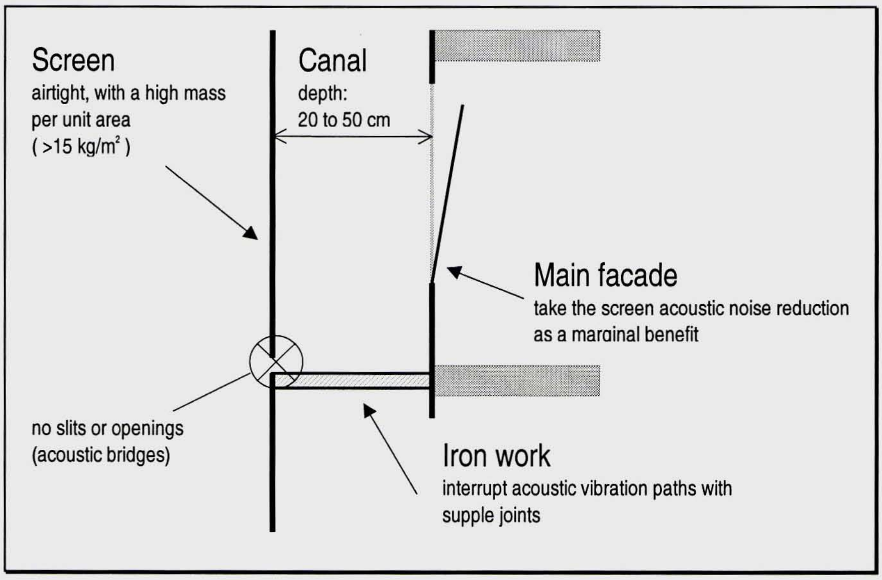


The other side of the coin is that a double-skin facade can favour noise propagation from one part of the building to another when the windows are opened. To avoid this effect, it is worthwhile closing the canal at the unit borders horizontally and vertically.

Daylighting

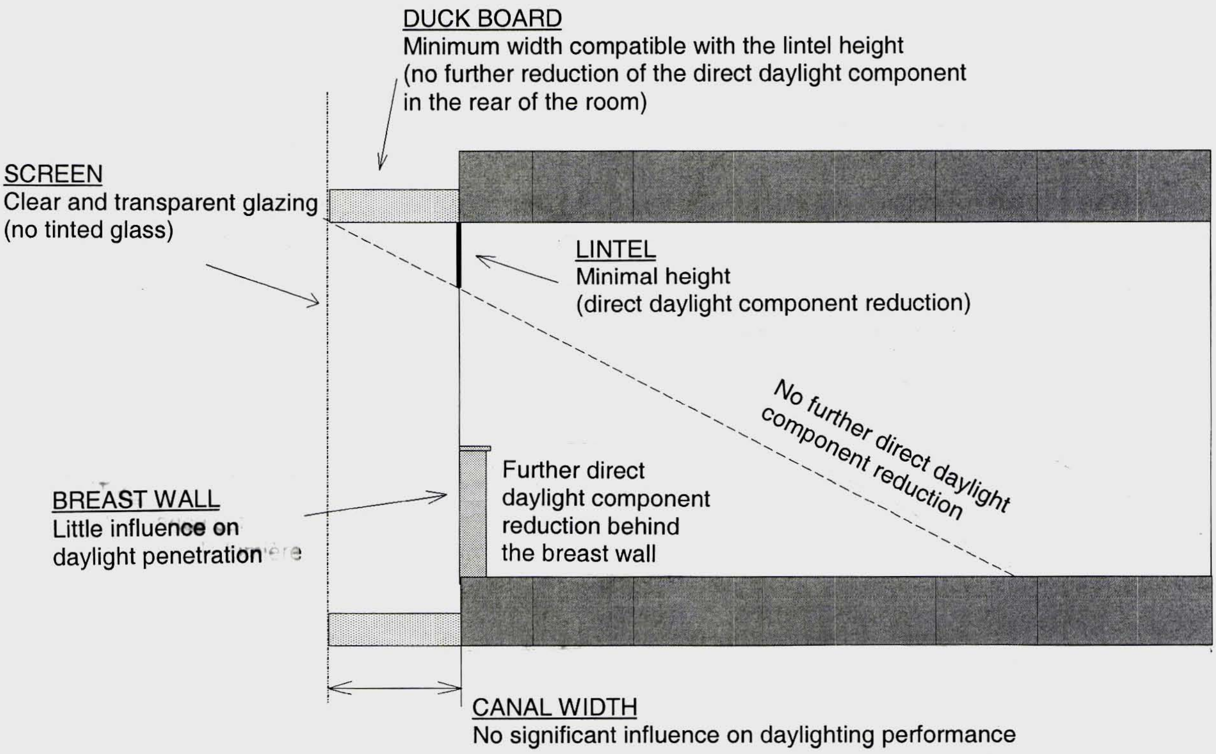
As far as daylighting is concerned, there is no significant difference between double-skin and conventional facades, where the following parameters define daylighting performance:
- daylight factor distribution,
- annual daylight autonomy fraction,
- visual ambience in the room.

In no case should a double-skin facade be assimilated to a daylighting system that improves daylight penetration into the room.

The rules that are commonly used to design daylighting through conventional facades may be applied to double-skin facades, as well. This has been confirmed through numeric simulation of double-skin facades.

The main precautions to be taken in order to avoid that a double-skin facade penalises daylight penetration into a room are the following:

- use clear glazing (light transmission factor of over 80%) for the main facade as well as for the screen (never use tinted glazing);
- reduce as much as possible the frame area of the windows (on the main facade as well as on the screen)
- pay special attention to the upper lintel of the facade window (which greatly influences the daylight penetration into the room) and reduce to a minimum its distance to the ceiling;
- choose the duck board width according to the lintel height (for example 18 cm width for a lintel that is 25 cm high) in order to avoid a further reduction of the diffuse (direct) daylight component form the open sky;



The distance between the screen and the main facade has no significant influence on daylight penetration into the room. Because of its low position, a breast wall only slightly reduces daylight penetration.

As the double-skin facade is by no means a daylighting system, the room daylight autonomy is comparable to that obtained from a conventional facade with breast wall and double (or triple) glazing. Daylight autonomy is restricted: only the first half of the room benefits from some autonomy in the case of double glazing. In the case of a tinted glazed screen, less than one third benefits from it; this type of glazing is therefore to be avoided.

For more detailed information, consult the file on "Daylighting".

4.3 Double-skin facade that provides natural room ventilation

If the double-skin canal stack effect is used to provide the natural ventilation of the rooms, the general properties (repeated hereafter) are the same as those presented in the former paragraphs. Additional precautions have to be taken, however, for the system to work correctly.

- ***Night time thermal insulation - U value computation***
  The inner facade thermal insulation is enhanced by the presence of the screen. The air movements in the double-skin canal nevertheless limit the gains to be expected and this even if the air movements are limited by closing the valves at the different floor levels.

  The U value of the double-skin facade can be computed in the usual way if one takes the data given in Table 4.1.1 for the thermal heat transfer coefficient of the canal. These only weakly depend on the canal height or discharge coefficient C_d.

- ***Clear Sky Radiation***
  As shown by Th. Franck [10], the building heat loss to the clear sky gives rise to supplementary heat losses with an intensity that is independent of the outdoor or building temperatures.

The practical rules are the following (see also 7 Establishing the Practical Rules).

U value computation

- The U value is computed in the usual way and gives the thermal heat transmission factor (per unit area) from the inside to the environment and outdoor air (see preceding §).

Supplementary heat losses to the clear sky

- Vertical surface radiation to the clear sky gives rise to supplementary heat losses ΔR of about 25 [W/m^2] for a partly overcast sky. Large discrepancies around this mean value are observed starting at 0 (heavily overcast sky) and rising to 60 [w/m^2] (clear sky, dry air).
  These values have to be nearly doubled for a horizontal surface.

- Heat losses to the clear sky are partly drawn from the facade itself and partly from the outdoor air (through heat exchange with the outdoor air)

- The *relative* rise of the facade heat losses (relative U value change) only depends on the temperature difference $\Delta T = T_{indoor} - T_{outdoor}$. It accounts for 8% in the case of a 20 [K] temperature difference without any reference to the particular wall U value.

- The *absolute* rise of the facade thermal losses [W/m^2] is by contrast proportional to the U value and to ΔR. If U = 1 [W/m^{2}K] and ΔR = 25 [W/m^2], then one expects a 1.64 [W/m^2] supplementary heat loss and this without any reference to the indoor to outdoor temperature difference.

- ***Behaviour in the cold season – Thermal comfort***
  The insulation quality offered by a double-skin facade depends foremost on the insulation quality of the *inner wall*. It is therefore recommendable to equip the internal wall with high-performance glazing mounted on a highly insulated breast wall and frames. This is the only condition for the double-skin facade to perform better than an equivalent simple facade (i.e. with the *same total number* of glazed surfaces with the same selective layers).

  If there is no breast-wall, there are considerable solar gains. Added to the internal gains (occupants, machines and lighting), they suffice to compensate the losses (by conduction through the facade and by ventilation) as soon as the meteorological variable m (Table 4.1.2) exceeds 3,5 [W/m^{2}K] (with artificial lighting) or 5 [W/m^{2}K] (without artificial lighting). For larger m values, a solar shading system is necessary (Table 4.1.3). A detailed justification of these data is presented in Chapter 8, Parametric Studies.

- ***Summer shading – summer comfort***
  Compared to a single facade, the double-skin facade is more likely to experience overheating and should consequently be fitted with an effective shading system that is located in the double-skin canal and well ventilated through the air circulating in the double-wall canal. There is no advantage in using the screen as a permanent solar protection: reflecting or absorbing, it only imperfectly reduces unwanted solar gains but hampers the desired daylight and reduces the daylighting autonomy.

  A blind (canvas or slat) reduces the heat gains by a factor 3 to 5 depending on the outdoor temperature and radiation: the greatest efficiency is observed when the outdoor temperature is lower than the room temperature and solar radiation is limited.

  For all solar radiation in excess of 100 W/m^2, the surface temperature of the indoor glazing is higher than the room air temperature. The effect of the blind is to lower this temperature by 1 or 2°C (and to cut direct radiation).

  The dynamic (time dependent) behaviour of the room - and thus the comfort experienced in clear hot weather - is strongly related to the room ventilation scheme and its thermal inertia. There is a clear benefit in restricting the solar gains by reducing the (internal wall) glazed area and in delaying the heat gains through the opaque parts by prolonging the thermal time delay of the breast wall.

- **Room ventilation**
  Air extraction form the rooms to the double-skin canal is not obtained by opening the windows but by opening valves sized floor by floor and located above the windows.

  The double-skin canal acts as the "engine" of room ventilation. Correctly sized, it allows cross ventilation: fresh air enters the room from the corridor and polluted air is sucked into the canal through floor valves.

  The air change rate adjusts automatically to the solar radiation intensity.

  The sizing of the canal is given under 4.4.

- ***Condensation risk***
  A well insulated internal facade fitted with high-performance glazing and framing does not show any condensation risk on its indoor surface.

  By contrast, in cold weather with a clear sky, there is a condensation risk on the outdoor surface of the internal facade as well as on the screen. This annoyance common to highly insulated building envelopes generally vanishes in the morning.

4.4 Recommendations : Double-skin facade providing room ventilation

☐ **Screen**
Clear glass is used for screen glazing without or with a minimum frame. It is airtight and extends 2 or 3 meters above the last ventilated floor level.

☐ **Internal facade (main facade)**
High thermal performance glazing (U < 1,6 W/m^2K) with high daylight transparency is worthwhile in winter as well as in summer. It is mounted on airtight frames with a thermal resistance that matches the U value of the glazing. Thermal comfort is enhanced by a correctly chosen glazed fraction. The choice should be dictated in priority by the daylighting needs (see Daylighting). The breast wall thermal resistance should be high (U < 0,5 W/m^2K) with a thermal delay of about 8 hours.
Depending on the screen and canal design, the required acoustic insulation will have to be provided by the internal facade alone (see Acoustic aspects).
Valves located above the windows and sized floor by floor allow the outflow of polluted air via the double-skin canal (fresh air inlets are planned on the corridor side of the rooms).
By opening the ventilation valves, noise propagation in the double-skin canal and from there in the neighbouring rooms or floors is favoured (see Acoustic aspects).

☐ **Double-skin canal**
The canal upper aperture is sized according to the following data :

- canal extension h_t over the last floor ventilation valve,
- ventilated volume per floor and linear facade length (1 meter)
- number N of ventilated floors,
- solar intensity transferred to the air G_{air}.

This aperture determines the canal sizing.

The working part ("engine") of the natural ventilation of a shaded facade is the "engine capacity" $A_{sup} \cdot h_t$ driven by the intensity G_{air} transferred to the air. Sizing the system can be achieved by using abacus or spreadsheet programming. It is worthwhile to notice that the air change rate is going to adjust automatically according to the solar radiation intensity changes. The air temperature in the canal is equal or slightly superior to that of the air extracted from the rooms. The temperature rise in the sunlit upper part of the canal can be computed (equation (9), §3.2.1) or read on an abacus.

When the facade is unshaded the whole canal height is subject to a stack effect and the "engine capacity" is now

$$A_{\text{sup}} \cdot \sqrt{h_t \cdot h_{\acute{e}tage}} \ .$$

Again the maximum number of ventilated floors or - if this number is given - the corresponding "engine capacity" can be evaluated through an adequate abacus or computed with a spreadsheet program.

The air temperature in the canal of an unshaded double-skin facade rises at every floor level and may therefore become the limiting factor to the possible number of naturally ventilated floors. This temperature rise is again computable (equation (9), § 3.2.1); it can also be read on an abacus.

Sounds are propagated horizontally and vertically by the double-skin canal, which may lead to acoustic troubles (see Acoustic aspects).

☐ **Shading systems**

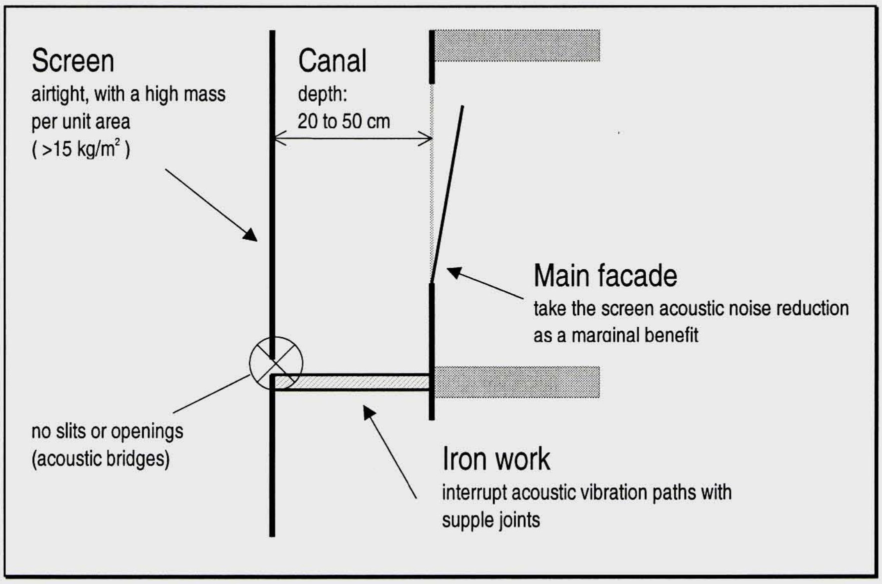
Effective shading systems (canvas or slat) are mandatory. For practical (and esthetical) reasons they are located inside the double-skin canal. They are placed at a certain distance from the facade in order to favour air circulation.

☐ **Acoustic aspects**

Well planned, a double-skin facade improves protection against outdoor noise. This effect may also be noticeable when the windows are open. Nevertheless, depending on the way the screen is implemented, there may be no additional outdoor noise reduction at all.
Forecasting the acoustic noise reduction of a double-skin facade is a complex matter because many parameters have to be taken into account. It is wrong to think that the overall noise reduction of the facade is obtained by adding the noise reduction of the screen to the noise reduction of the main wall.
For this reason, it is risky to plan reduced noise reduction values for the main facade without consulting an acoustics engineer.

In order to improve the outdoor noise reduction performance of a double-skin facade, the following rules have to be followed:

- Plan an airtight screen, i.e. there should be no direct sound propagation path from outdoors to the canal: openings, slits between elements, etc. are phonic bridges.
- The screen should be made of a sufficiently heavy and/or thick material in order to obtain as high as possible a mass per unit area - typically over 15 kg/m^2; nevertheless, if the thickness exceeds 5 mm, a stratified structure is preferable.
- Choose a canal depth between the airtight screen and the main facade of between 20 and 50 cm.
- In order to avoid that vibrations propagate through the iron work from the screen to the main facade, supple joints should be used.



The other side of the coin is that a double-skin facade can favour noise propagation from one part of the building to another when the windows are opened. To avoid this effect, it is worthwhile closing the canal at the unit borders horizontally and vertically.

☐ Daylighting

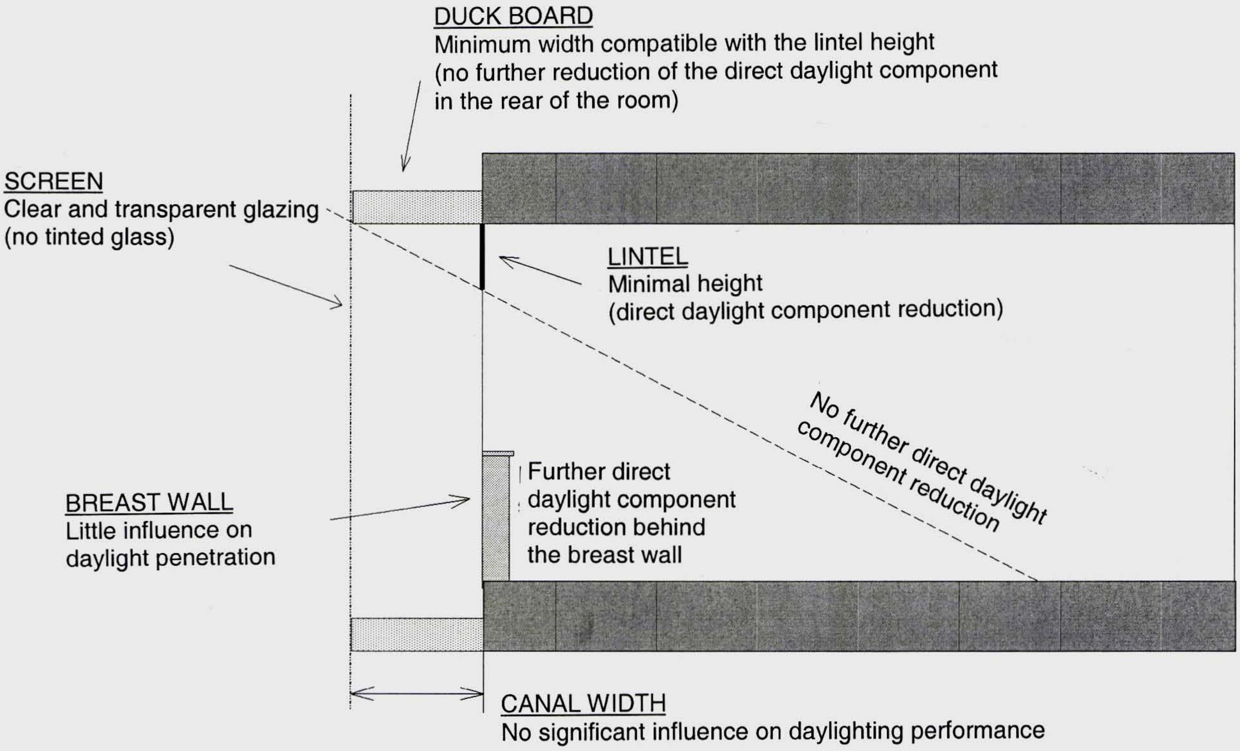
As far as daylighting is concerned, there is no significant difference between double-skin and conventional facades, where the following parameters define daylighting performance:
- daylight factor distribution,
- annual daylight autonomy fraction,
- visual ambience in the room.

In no case should a double-skin facade be assimilated to a daylighting system that improves daylight penetration into the room.

The rules that are commonly used to design daylighting through conventional facades may be applied to double-skin facades, as well. This has been confirmed through numeric simulation of double-skin facades.

The main precautions to be taken in order to avoid that a double-skin facade penalises daylight penetration into a room are the following:

- use clear glazing (light transmission factor of over 80%) for the main facade as well as for the screen (never use tinted glazing);
- reduce as much as possible the frame area of the windows (on the main facade as well as on the screen)
- pay special attention to the upper lintel of the facade window (which greatly influences the daylight penetration into the room) and reduce to a minimum its distance to the ceiling;
- choose the duck board width according to the lintel height (for example 18 cm width for a lintel that is 25 cm high) in order to avoid a further reduction of the diffuse daylight component form the open sky;



The distance between the screen and the main facade has no significant influence on daylight penetration into the room. Because of its low position, a breast wall only slightly reduces daylight penetration.

As the double-skin facade is by no means a daylighting system, the room daylight autonomy is comparable to that obtained from a conventional facade with breast wall and double (or triple) glazing. Daylight autonomy is restricted: only the first half of the room benefits from some autonomy in the case of double glazing. In the case of a tinted glazed screen, less than one third benefits from it; this type of glazing is therefore to be avoided.

For more detailed information, consult the file on "Daylighting".

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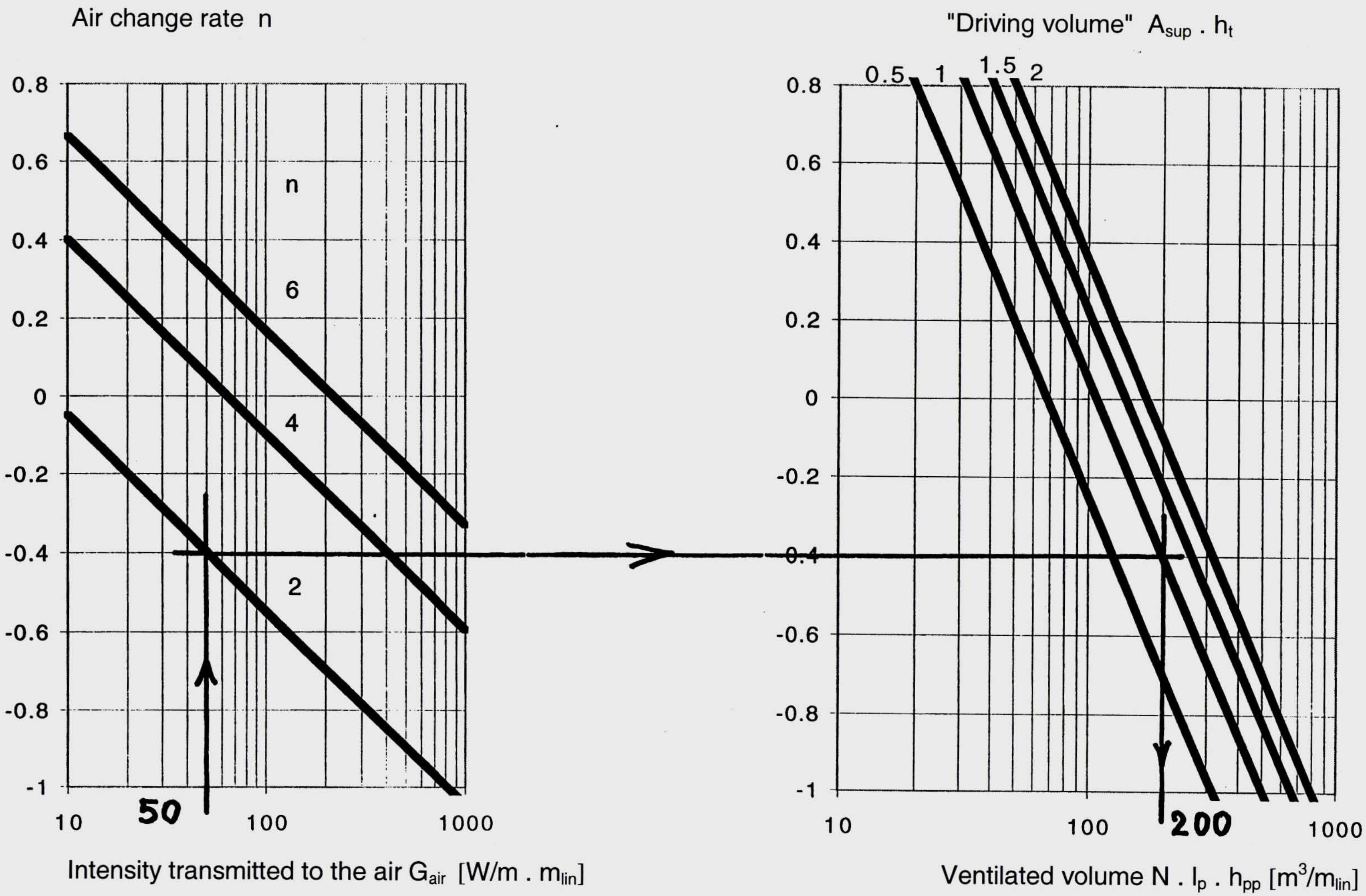
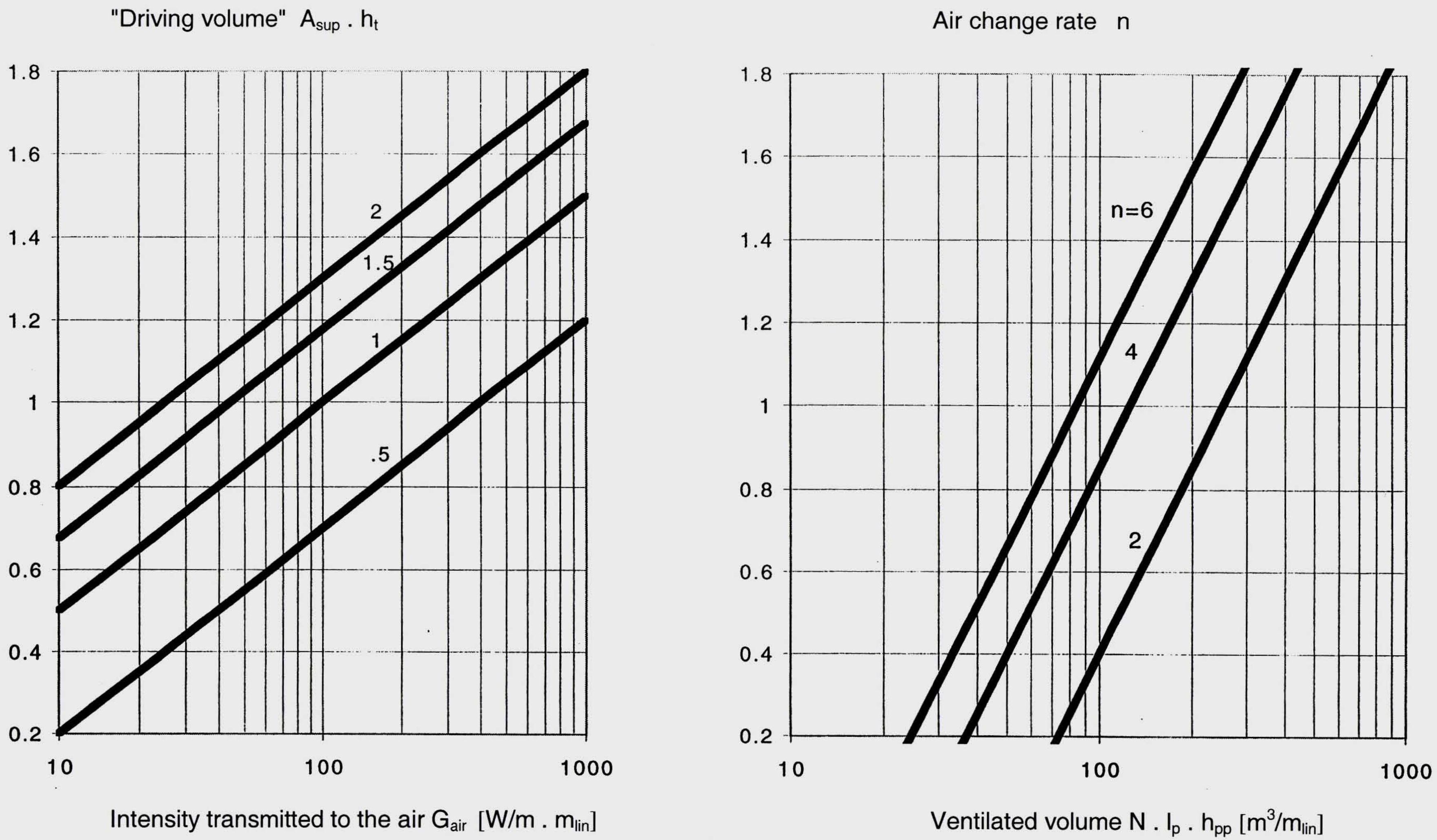
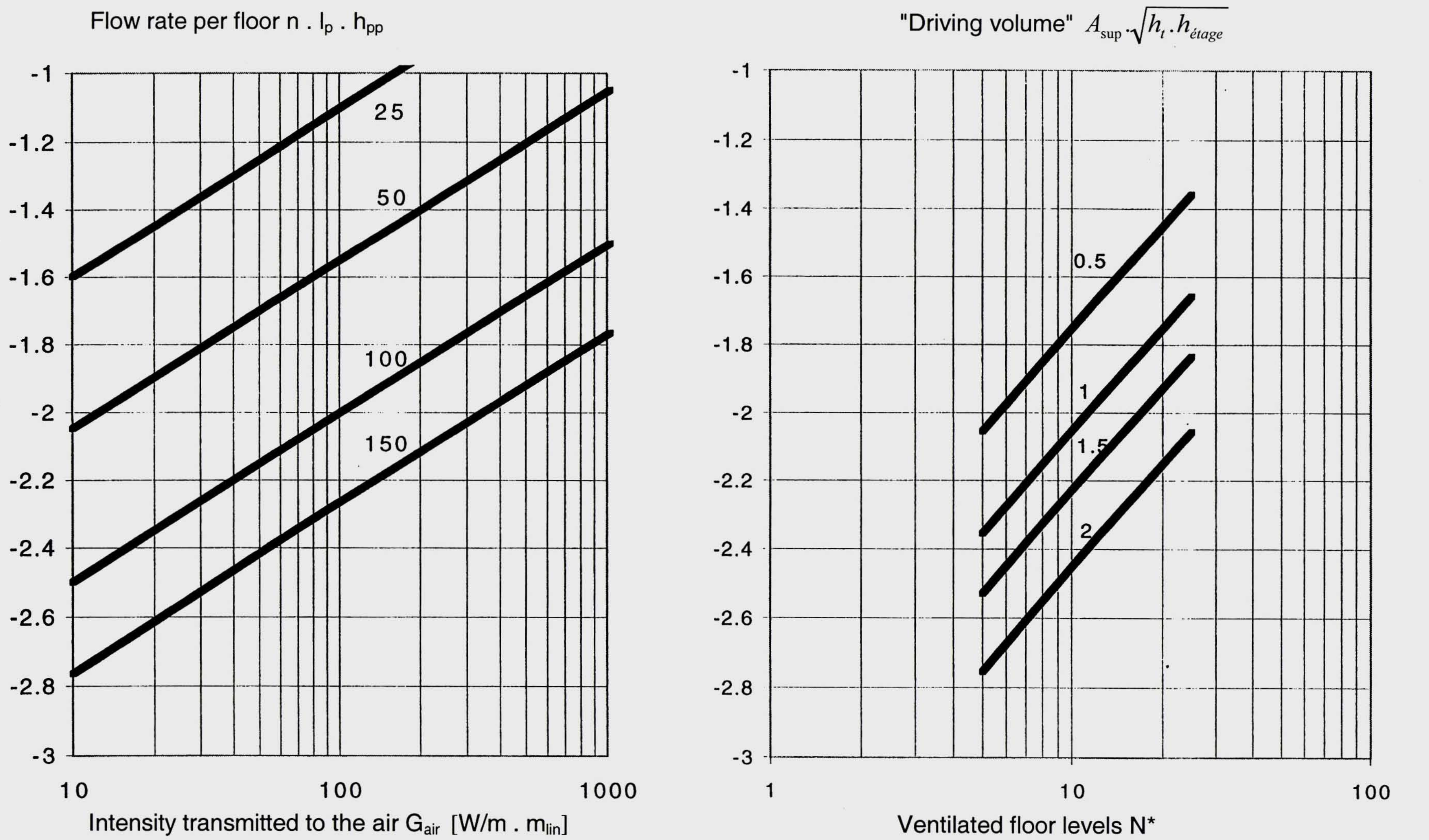


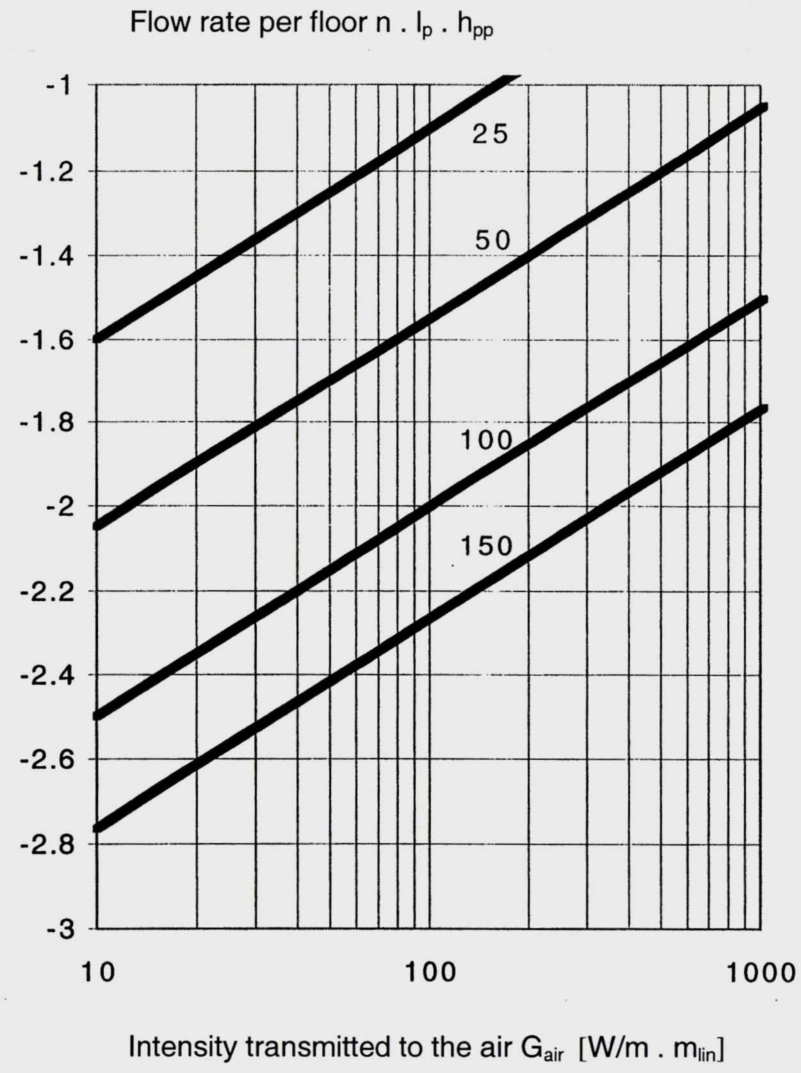
Abacus 4.4.1 : Natural cross ventilation through the double-skin. Shaded facade.
Volume ventilated by the double-skin as a function of geometric and energy-related characteristics.
The air change rate n is expressed by [1/h]. The effective upper section is $A_{sup} . A_H . C_{d,H}$.
The " driving volume" $A_{sup} . h_t$ is expressed in [m^3/m_{lin}]

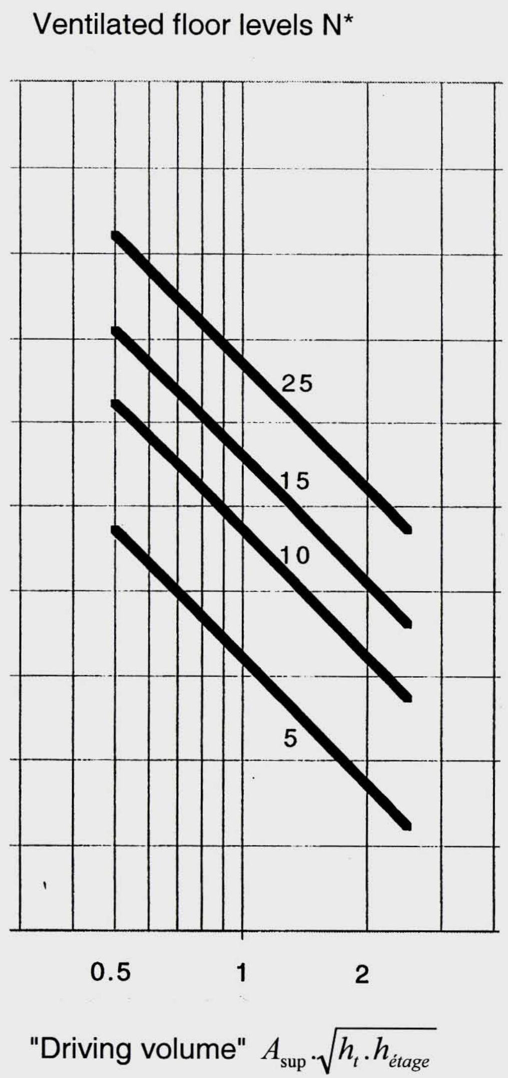


Abacus 4.4.2 : Natural cross ventilation through the double-skin. Shaded facade.
Volume ventilated by the double-skin as a function of geometric and energy-related characteristics.
The air change rate n is expressed by [1/h]. The effective upper section is A_{sup} . A_H . $C_{d,H}$.
The " driving volume" A_{sup} . h_t is expressed in [m^3/m_{lin}]

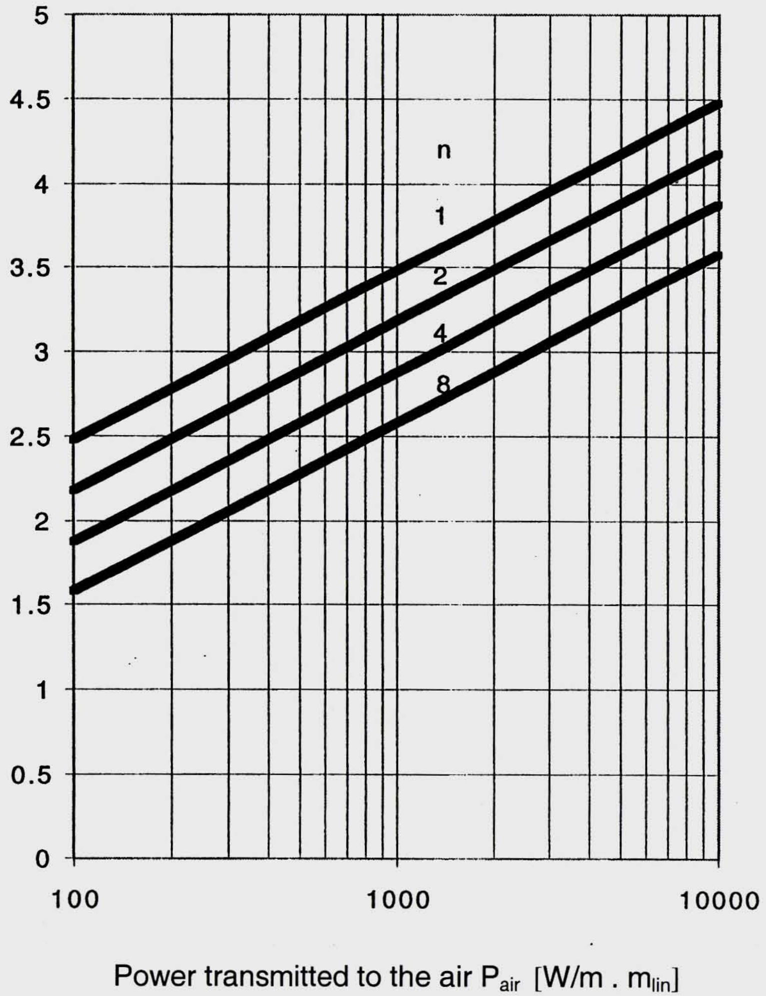


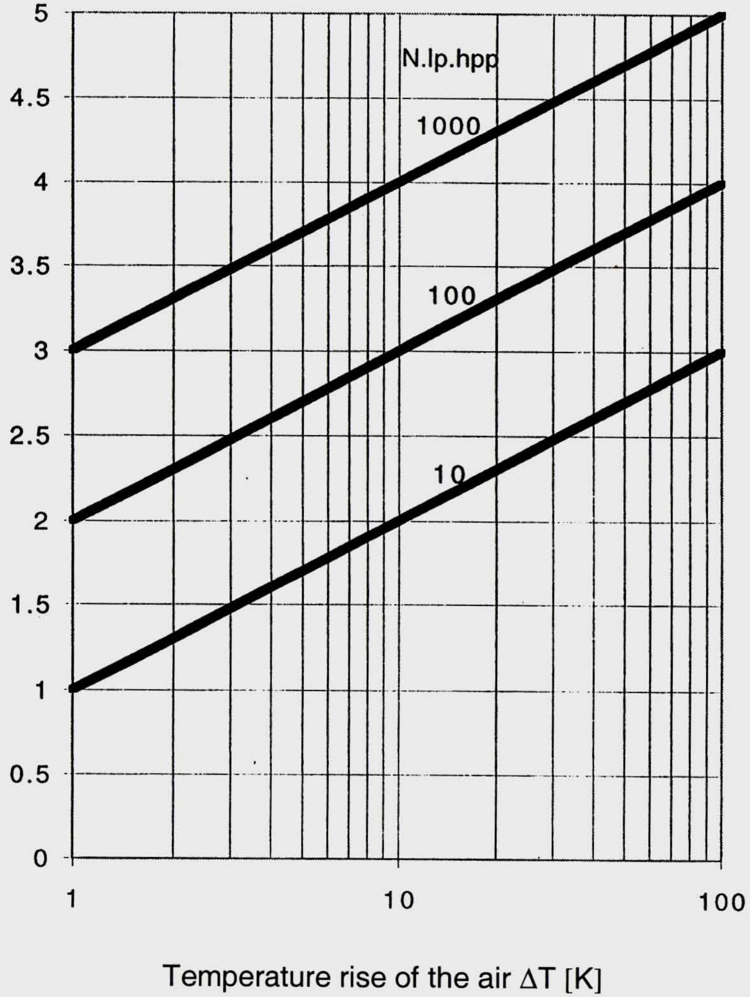
Abacus 4.4.3 : Natural cross ventilation through the double-skin. Unshaded facade.
The ventilation capacity depends on the flow rate per floor n . l_p . h_{pp} [m^3/h m_{lin}] and the driving volume $A_{sup} \cdot \sqrt{h_t . h_{étage}}$ [m^3/m_{lin}].
The maximum number of floors that can be ventilated is $N = N^* + h_t/2\ h_{étage}$.





Abacus 4.4.4 : Natural cross ventilation through the double-skin. Unshaded facade.
The "driving volume" needed for the ventilation of N floor levels depends on the flow rate per floor level $n \cdot l_p \cdot h_{pp}$ [$m^3/h\ m_{lin}$] and the number of floors $N^* = N + h_t/2\ h_{étage}$.





Abacus 4.4.5 : Estimate of the air temperature rise in the double-skin canal.
The power transmitted to the air is given by G_{air} . h where h is the unshaded height (h_t ou H).
n is the air change rate in the ventilated volume [1/h].
N . l_p . h_{pp} is the ventilated volume [m^3/m_{lin}].

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Table of contents

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