Development of numerical shading devices models for the use in building thermal simulation

Jean NOËL

Jean NOËL (JNLOG)
Free-Lance Engineer
15 place Carnot
69002 Lyon
France

Report n° 0402

Table of contents

Abstract

Building envelope performance is strongly influenced by solar gain and heat transfer through windows. The majority of this energy gain or loss passes through the center-glass area of the glazing system. It is thus important to model accurately the thermal and radiative behaviour of this part, in order to control the energy exchanges as well as possible.

In addition, the adding of solar devices to windows is more and more widely used, in order to ensure thermal comfort or to minimise mechanical cooling loads. Then proper shading devices can be partially or fully paid for by reduced cooling equipment and cooling energy costs.

This complex assembly is difficult to represent, and few tools or methods make a complete treatment of it.

The presented methodology here establishes the whole of the optical and thermal relations of a glazing associated with a solar protection. The models presented can lead to very precise results or simpler models usable in dynamic computation software, according to the degree of accuracy desired. These models are not very new, but they are gathered here for a simultaneous use in building thermal simulation.

This methodology was implemented in the development of classes of objects, with an object-oriented modelling. These classes were integrated in a program, which is used for the validation of the theory. These same classes were also integrated in the software CoDyba [CDB] to allow the dynamic simulation of a building having windows with shading devices.

The data as well as the general findings shall serve the public in fenestration and building industry through later publication.

I - Introduction

I - 1 - Background

Optimal use of daylight and solar heat gains in buildings is made possible by the use of adequate sun-shading systems. This implies that sun-shading systems must be able to control and regulate solar gains through facades.

Presently, there are no reliable standard methods to evaluate the effectiveness of sun-shading systems. Indeed, the interaction of these two parts is complex and depends on a great number of parameters related on the glazing and the shading device. Moreover, some of the parameters are variable in time, like the position of the position of the sun compared to the glazing or the configuration of the shading device (angles of the slats for a blind, for example). All that made that it is impossible to obtain easily a simple model.

It should be noted that it is not enough to consider the part of solar radiations transmitted directly by the glazing unit, but the part of energy that is actually transmitted. Indeed, a considerable fraction of the energy absorbed by the glazing unit is restituted to the indoor by heat conduction.

The search for a simplified model is not necessary, while current computer offers the opportunity to employ more detailed and accurate models. Moreover, in this case the whole of the parameters of the systems can be taken into account.

The objective of the current project has been the development of a methodology for complex glazing and integrated shading elements. This methodology is applied in the building dynamic simulation software CoDyBa ([CDB]).

The report is divided in three parts. The first part presents the optical relations of a semi-transparent multi-layer assembly, while the second part describes its thermal relations. The third part compares obtained results to other published in the literature.

This report is a provisional report, which will be completed and detailed later.

I - 2 - The window parameters U and G

The two main parameters of a window are the coefficients U and G :

The window G-value : it indicates which fraction of the incident solar radiation is absorbed and transmitted by the window and becomes heat in the building. It includes both the primary and secondary transmittance i.e. the energy absorbed by the glazing and redirected to the building interior.

The window U-value : it represents the inverse of thermal resistance between the indoor air and the external environment.

In this report, only the relations concerning G-value will be developed.

The physical mechanism at the base of the definition of G-value is as follows: the absorbed radiation is turned to heat inside the absorbing material (glass or shading device), and the glazing loses the heat through conduction, convection and radiation. Some heat goes outside the building, and the remainder adds to the directly transmitted solar heat gain.

Fig. 1 illustrates the meaning of G for the example of an integrated venetian blind. A G-value of 0,3 means that 30% of the incident radiation is transmitted into the building.

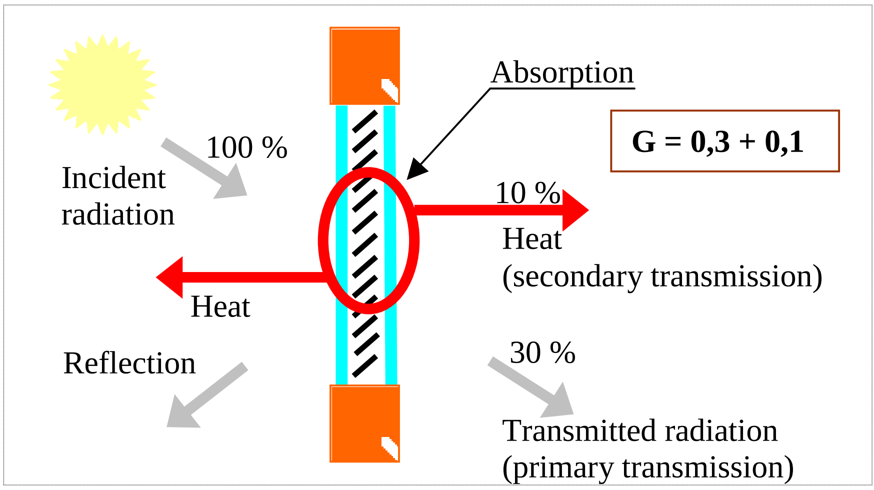


Fig. 1 : explanation of the total solar energy transmittance G-value

If E is the incident solar irradiance (outside), τ is the solar transmittance, α is the solar absorptance and N is the inwardly flowing fraction of the absorbed irradiance, the solar gain q (inside) is :

$$q = G.E \quad \text{and} \quad G = \tau + [N.\alpha] \qquad \text{(Eq. 1)}$$

G is the solar heat gain coefficient (SHGC, or G-value). It is the fraction of incident irradiance that enters through the glazing as heat gain. It includes both the directly transmitted portion τ and the absorbed and reemitted portion $N.\alpha$. The G-value is needed to determine the solar radiant heat gain from a window, and should be included, along with window U-value in any description of a window's energy performance.

A "good" shading device has a low G-value since only a small fraction of the incident radiation is absorbed and transmitted as light or heat into the room. A "poor" shading device has a high G-value since it let's most of the incident radiation flowing into the building.

There are two fundamentally different methods to determine the G-value of a window :

Direct measurements : in this procedure, the G-value is measured directly. This is done by irradiating the window either with sunlight or a solar simulator. Behind the window, the transmitted energy is determined calorimetrically.

Calculation methods : all of these methods start with the optical properties of the different layers of the window.

The exact G-value depends on these boundary conditions:

1. Position of the blind (internal, integrated or external).
2. Glazing and type of blind.
3. Wind conditions.
4. Ventilation of the gap between the blind and glazing.
5. The direction of the incident radiation. The surface of the window is irradiated directly and diffusely from different directions. The luminance distribution of the sky and the ground depends on the weather conditions and the building's surroundings (e.g. ground reflectance, shading from other buildings, etc.).

The G-value varies according to the sun's incidence angle with respect to the window's normal (see fig. 2).

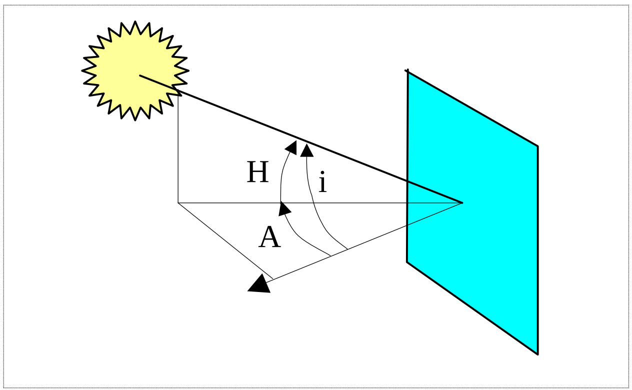


Fig. 2 : schematic description of solar angles

A is the solar azimuth and H is the solar height. i is the sun's incidence angle.

To determine a model giving this G-value, one will proceed in two stages. First, an optical analysis determines how much of the incident solar radiation is absorbed at each of the glazing layers and how much is transmitted into the indoor space. Second, a heat transfer analysis is used to impose an energy balance on each glazing layer.

Note that it is usual to treat G-value only for direct radiations. In fact, it is necessary to consider the direct and diffuse radiations, and to determine corresponding G-values : it is what will be made here.

I - 3 - Implementation

Classes are developed in order to represent shading devices, window, and their interactions. The classes were tested separately, first step-by-step, and finally together, with comparisons with results found in scientific papers.

The classes were then integrated in CoDyBa software. CoDyBa ([CDB]) is a dynamic building energy analysis program, originally from INSA, but continuously improved at by Jean NOËL. It currently runs on a PC in the window environment.

II - Modelling

II - 1 - Position of the problem

II - 1 - 1 - Different types of shading devices

Shading devices can be divided into two basic types:

1. Layer type of shadings, such as screens, curtains and venetian blinds that are located parallel to the panes, with intimate thermal-optical contact.
2. Extra-fenestrial type of shadings, such as awnings and overhangs that are located less close to the panes, with limited thermal-optical contact.

Although there is no sharp cut distinction between the two types of shadings, the extra-fenestrial types of shadings may be regarded as part of the window's environment, because of the limited thermal interaction.

This report doesn't deal with the extra-fenestrial type of shading.

II - 1 - 2 - One-dimensional treatment of an assembly of semi-transparent parallel layers

The next analysis has been carried out on the basis of the following assumptions :

1. The transport of solar radiation and heat is considered to be one-dimensional.
2. Effects of window edges are neglected.
3. The solid layers are assumed to be homogeneous with a thermal resistance. Each glazing layer is flat and specular.
4. The solar and optical layer properties are independent of the intensity of the solar irradiation and temperature in the system.
5. The gas spaces are completely transparent, without any absorption. Ventilated spaces are ignored.
6. Blind has no mass.
7. Blind slats (if the blind is a venetian blind) are parallel and horizontal, and have no mass and null thickness. The slats are non-specular reflecting. Each slat receives the same irradiation. Due to assumption of non-specular reflection a slight curving of the slats may be neglected.
8. The evolution time of a window component is small in comparison of evolution time of the thermal conditions of the part and the evolution of the external conditions. In other words, one will suppose the thermal balance reached for these components. Indeed, characteristic times of the external walls are of about an hour.

II - 2 - Optical modelling of an assembly of semi-transparent parallel layers

II - 2 - 1 - Definitions

II - 2 - 1 - 1 - Definition of a *layer*

Definition : a layer is a thermo-optical element, which acts in a one-way direction on the solar radiation.

The parameters associated with a *layer* are :

1. R : thermal resistance
2. M : surface density

The density M is not used as such, but makes it possible to "type" the surface.

<u>Particular case of a glass</u> :

Beam radiation transmitted or reflected by the solar shading device is considered to be split into two parts :

1. a undisturbed part (specular transmission and reflection)
2. a disturbed part (the disturbed part is approximated as anisotropic diffuse, Lambertian)

Particular case of a shading device :

The layer type of shading may be defined in the model as a layer between two gaps ([163] chap. 7.1.2). This layer exchanges heat with the other components and the environment by conduction and convection, and by thermal radiation. It also absorbs, reflects and transmits solar radiation.

Diffuse radiation transmitted or reflected by the solar shading device is assumed to remain diffuse.

Particular case of far shadows :

Due to the redirection of the radiation the forward transmittance is not necessarily equal to the backward transmittance.

II - 2 - 1 - 2 - Definition of a layer's *face*

Definition : a face is associated to layer for one of the two directions of the radiations, knowing that the treatment is one-dimensional. The letters L and R characterise the two faces of the layer.

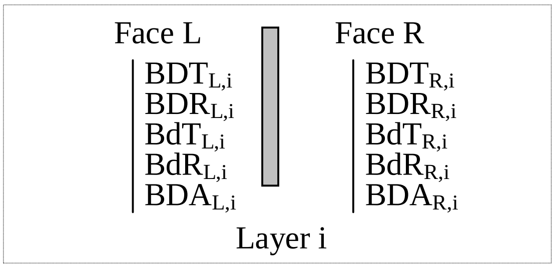


Fig. 3 : *layer's* data

The main optical parameters associated with a layer face are the following ([163] chap. 7.2, [LUND] p. 71) :

1. BDT : direct-direct transmittance (direct transmittance)
2. BDR : direct-direct reflectance (specular reflectance)
3. BdT : direct-diffuse transmittance (diffuse transmittance)
4. BdR : direct-diffuse reflectance (diffuse reflectance)
5. BDA : direct-direct absorptance (absorptance)

6. dT : diffuse-diffuse transmittance
7. dR : diffuse-diffuse reflectance
8. dA : diffuse absorptance

9. BDT+BdT : direct-hemispherical transmittance (derived parameter)

'Diffuse' here means isotropicaly diffuse. 'Direct-diffuse' means that the incoming radiation is direct and the outgoing radiation (after interaction with the layer) is diffuse ([LUND] p 71).

Letters L or R distinguish the coefficients associated with the faces. For example, BDT,R is the direct-direct transmittance for the direct radiation and for the face R (for the radiation going from the Right towards the Left).

'Direct' parameters are the main data, while 'diffuse' parameters are normally calculated according to the principal parameters. Indeed the diffuse coefficients of a layer depend at the same time on the properties of the layer and the angular distribution of the diffuse radiation

For most ordinary glazing, the 'direct-direct' transmittance (BDT) is maximum around the normal angle of incidence, starts declining at 50 ° and becomes zero at 90°.

The 'direct-direct' reflectance (BDR) represents the reflection in the direct form of a direct radiation. In the case of a solar protection of type 'venetian blind', it is taken null ([TC163] chap. 7.3.2, eq. 89).

Note that one places oneself in the field of the visible radiations, and one supposes that the characteristics don't depend on wavelength. In the contrary case, one would need to share the spectrum in several parts and to apply to each one of them the current methodology.

<u>II - 2 - 1 - 3 - Definition of a *sandwich*</u>

Definition: a sandwich corresponds to a whole of layers semi-transparent, i.e. in an array of solid layers separated by air or gas filled spaces.

The total radiative coefficients (coefficients of the layer that is equivalent to the *sandwich*) are identical to those of a layer.

The following specific coefficients are added to the *sandwich* :

1. BG : G-value for direct radiation
2. dG : G-value for diffuse radiation
3. BA_GTF : global direct absorption coefficient for the first face of the equivalent layer
4. BA_GOF : global direct absorption coefficient for the last face of the equivalent layer
5. dA_GTF : the same as BA_GTF but for diffuse radiation
6. dA_GOF : the same as BA_GOF but for diffuse radiation

These coefficients are again defined for two directions: one of Left towards Right and the other of Right towards Left.

<u>II - 2 - 1 - 4 - Definition of the *sandwich* which is equivalent to a window</u>

By extension, one can define a *sandwich* equivalent to a glazing, by taking of account the cover ω of solar protection. Conceptually:

$$Sandwich(\omega) = (1-\omega) * Sandwich\_without\_sh.d. + \omega * Sandwich\_with\_sh.d. \qquad \text{(Eq. 2)}$$

where ω denotes the fraction of the glazed part of the window which is covered by the shading device.

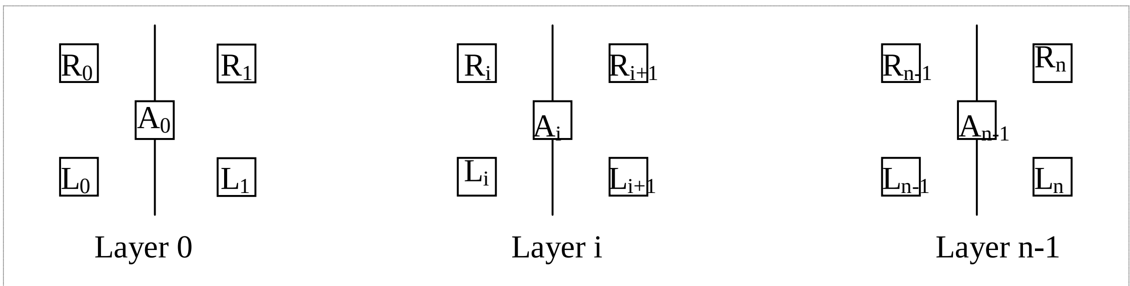
<u>II - 2 - 2 - Optical modelling of an assembly of semi-transparent parallel layers</u>

<u>II - 2 - 2 - 1 - General treatment of the problem</u>

The general treatment of the problem concerns only the direct radiation. The aim is to establish the direct coefficients of layer LS equivalent to a sandwich. The diffuse coefficients of this layer LS are then determined by integration on a half-sphere.

<u>II - 2 - 2 - 1 - 1 - Position of the problem</u>

A window with n glass layers together with the outdoor and indoor spaces form an n+2 element array. Then, one considers the vector formed by n layers. Each layer can be crossed of right-hand side to the left and of left to the right.



<u>Fig. 4 : *layers* in a *sandwich*</u>

Unknown are incident radiant energies on each layer i. Incident energies are subscripted L or R according to the face of incidence of the layer. In addition, letters B and d specify that the energy is direct or diffuse.

R_i is the incident radiant energy flowing from layer i-1 to layer i, L_i that from layer i to layer i-1. A_i i the radiant energy absorbed by the layer i. Moreover, letters B and d specify that the energy is direct or diffuse.

II - 2 - 2 - 1 - 2 - System to solve

The glazing system optical analysis can be carried out by considering the fluxes of radiant energy flowing from layer 0 to layer n-1 (see [WRI1] p. 1233) for a treatment of a window without blind).

From the optical coefficients of each layer, one establishes by layer a radiative energy balance. For example, the equation giving $R_{B,i}$ is :

$$R_{B,i} = BDR_{R,i-1} * L_{B,i} + BDT_{L,i-1} * R_{B,i-1} \qquad \text{(Eq. 3)}$$

The boundary conditions of the system are radiative energies of layer 0 in the direction 'right-to-left' and radiative energies of the n-1 layer in the direction 'left-to-right'.

The modelling leads to the resolution of a matrix system, whose unknown are incident radiative energies.

Once these radiative energies calculated, one deduces the *sandwich's* coefficients from them by elementary operations on calculated energies. For example, the direct transmittance is calculated as follows:

$$BDT_L = R_{B,n-1} / R_{B,0} \qquad \text{(Eq. 4)}$$

II - 2 - 2 - 1 - Treatment of diffuse radiation

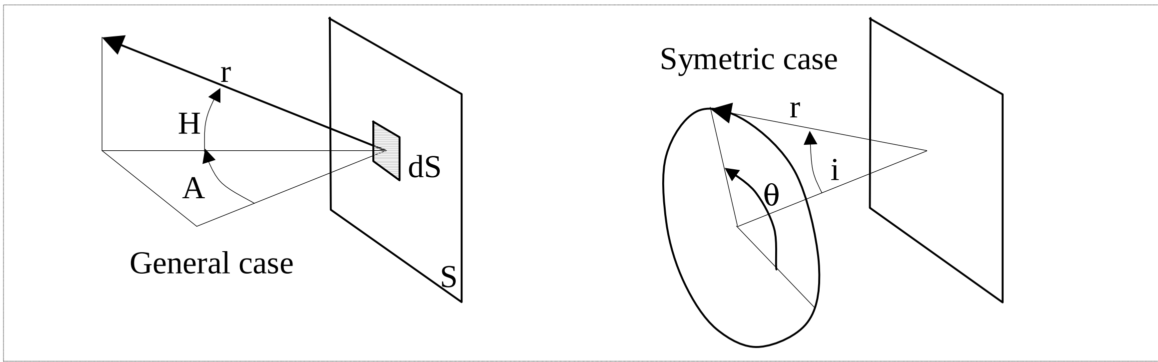


Fig. 5 : schematic description of the treatment of diffuse radiations

For diffuse radiation, integration is carried out on a half-sphere of ray r. The irradiation is supposed to be isotropic (the density D is constant).

$$\overline{dT} = \int_{i=0}^{i=\pi/2} BDT(i).\sin(2.i).di \qquad \text{(Eq. 5)}$$

The integration is carried out for the *layer* LS equivalent to the *sandwich*.

It should be noted that if one doesn't want to determine the diffuse radiation in this manner, one could use the method of the calculation of diffuse radiation with 60° of incidence ([ASH93] chap.27.18), provided that the system has a cylindrical symmetry, which is not the case if solar protection is of venetian blind type.

II - 2 - 2 - 3 - Specific treatment of shading device to obtain layer's data

II - 2 - 2 - 3 - 1 - Screen

The screen's coefficients are usually directly given.

II - 2 - 2 - 3 - 2 - Venetian store

The control volume considered for the radiative analysis is the cavity comprised within two adjacent slats (see [MAZZ] for a detailed description, or [TC163] ch. 7.3). The procedure is to consider two adjacent slats and to subdivide the slats into two elements (the norms [TC163] or [13363, Annex A] recommend to divide every slat into five elements, but the choice of 5 segments is not clarified in the norm). In the present model, the length of each part is adjusted to take into account of the solar irradiated fraction of the slat.

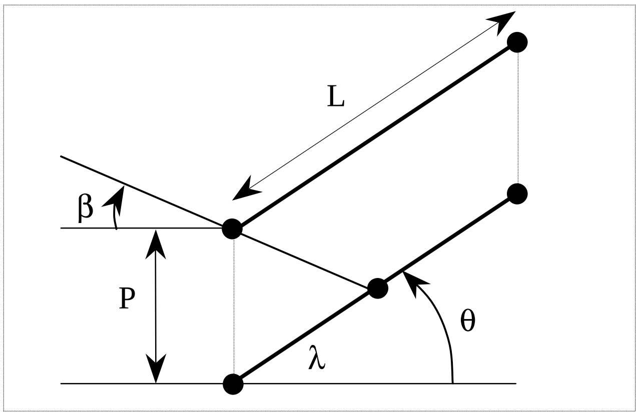


Fig. 6 : the cavity formed by two adjacent slats

There are two transmission modes : the primary transmission (beam solar radiation passing through the shading assembly) and the secondary transmission.

By geometric calculation from the angle θ and aspect ratio of the slats (P, L), the beam radiation (primary transmission) which passes the slats without touching can be calculated for a given angle of incidence β.

Due to assumption of non-specular reflection the values for the view factors can be calculated by conventional view factor methods for diffuse radiation exchange.

II - 3 - Thermal modelling of an assembly of semi-transparent parallel layers

II - 3 - 1 - Position of the problem

One position of the problem is presented by Wright ([WRI1] p. 1239).

In norm [TC163] chap. 7.4.2, an air node is placed between two solid layers: it is simpler from a conceptual point of view to treat the air in the same way than a solid layer. This air layer is transparent and has a thermal resistance.

II - 3 - 1 - 1 - Calculation of absorption coefficient GTF et GOF

These coefficients GTF ($\overline{\alpha}_L$) and GOF ($\overline{\alpha}_R$) are used for the calculation of the solar fluxes absorbed by each face of a glazing. In the following formulas, layers 0 and n-1 correspond respectively to the first layer and to the last layer of the *sandwich*.

$$\boxed{\overline{\alpha}_L = \alpha_0 + \sum_{i=1}^{n-2} \frac{\overline{h}_{i,0}}{\overline{h}_{i,0} + \overline{h}_{i,n-1}} . \alpha_i} \text{ (Eq. 6)} \quad \text{and} \quad \boxed{\overline{\alpha}_R = \alpha_{n-1} + \sum_{i=1}^{n-2} \frac{\overline{h}_{i,n-1}}{\overline{h}_{i,0} + \overline{h}_{i,n-1}} . \alpha_i} \text{ (Eq. 7)}$$

$$\text{with } \frac{1}{\overline{h}_{i,0}} = \sum_{k=SL0+1}^{i-1} R_k + \frac{1}{2} . R_i \text{ (Eq. 8)} \quad \text{and} \quad \frac{1}{\overline{h}_{i,n-1}} = \sum_{k=i+1}^{SLN-1} R_k + \frac{1}{2} . R_i \text{ (Eq. 9)}$$

SL0 and SLN represent the first and the last solid layer (glass or blind) of the *sandwich*.

These two coefficients are related by the relation : $\overline{\alpha} = \overline{\alpha}_R + \overline{\alpha}_L = \sum_{i=0}^{n-1} \alpha_i$ (Eq. 7) (see [WRI1] p. 1240).

II - 3 - 1 - 2 - Definition of the G-value

G-value is written (for a type of radiation, direct or diffuse) : $G = \tau + [N.\alpha]$ where $[N.\alpha]$ represents the energy absorbed by the *sandwich* and restituted to the interior volume of air (see Eq. 1):

$$[N.\alpha] = \sum_{i=0}^{n-1} \frac{\overline{\overline{h}}_{i,A}}{h_{i,O} + h_{i,A}} . \alpha_i \qquad \text{(Eq. 10)}$$

with $\frac{1}{\overline{\overline{h}}_{i,O}} = \sum_{k=0}^{i-1} R_k + \frac{1}{2}.R_i$ (Eq. 11) and $\frac{1}{\overline{\overline{h}}_{i,A}} = \sum_{k=i+1}^{n-1} R_k + \frac{1}{2}.R_i$ (Eq. 12)

where A and O mark respectively the nodes of internal and external air.

Taking into account that G-value expresses the exchanges between the node of outdoor air and the node of indoor air, it is necessary to sum on all the layers of the sandwich: in the formulas above, index 0 represents the first layer of the sandwich and n-1 the last (see [TC163], chap. 4.2.1 and [ISO9050] ch. 2.4.6.1).

III - Comparisons with results from the scientific literature

In the next data tables, h_e and h_i are respectively the external and internal thermal exchange coefficient.

III - 1 - NORM 13363-2

III - 1 - 1 - Treatment of a blind alone

A calculation is carried out for a blind alone whose slats are tilted at 45° and of which the ratio P/W=1. Sun azimuth A and sun height H are respectively 0° and 45°.

Case	Slat data		Results							
			Direct				Diffuse			
	τ	ρ	BDT+BdT		BDR		dT		dR	
			Norm	Present work	Norm	Present work	Norm	Present work	Norm	Present work
1	0,00	0,30	0,03	0,030	0,22	0,215	0,35	0,342	0,12	0,125
2	0,00	0,70	0,12	0,113	0,52	0,521	0,44	0,424	0,30	0,312
3	0,20	0,60	0,23	0,237	0,52	0,502	0,51	0,497	0,31	0,319

Table 1 : CoDyBa results compared to results given by the norm 13363-2 for a blind

Data and reference results are presented in [13363] p. 18 & 19.

III - 1 - 2 - Treatment of an integrated blind

III - 1 - 2 - 1 - Data

Case	Glass Data		Values	Notes
Glass				
Case	**Glass Data**		**Values**	**Notes**
Glass	absorption	α	0,11 (--)	[13363] p. 14
	reflection	ρ	0,07 (--)	[13363] p. 14
	transmission	τ	0,82 (--)	[13363] p. 14
	emissivity	ε	0,84 (--)	[13363] p. 14, note 4,
	conductivity	λ	1,15 W/m.K	missing data, completed
	width	--	4 mm	[13363] p. 14
Blind (*)	absorption	α	0,4 (--)	[13363] p. 23
	reflection	ρ	0,4 (--)	[13363] p. 23
	transmission	τ	0,2 (--)	[13363] p. 23
	emissivity	ε	0,9 (--)	[13363] p. 23
	conductivity	λ	--	
	width	--	--	
Window				
Case	**Window Data**		**Values**	**Notes**
All cases		h_e	20 W/m².K	Reference conditions
		h_i	3,6 W/m².K	[13363] p. 14
		h_e	8 W/m².K	Summer conditions
		h_i	2,5 W/m².K	[13363] p. 14
External			blind - 50 mm air space - 4 mm glass - 13 mm air space - 4 mm glass	
Internal			4 mm glass - 13 mm air space - 4 mm glass - 50 mm air space -blind	
Integrated			4 mm glass - 13 mm air space - blind - 13 mm air space - 4 mm glass	

Table 2 : Norm 13363 data summary for an integrated blind

(*) In this case, the blind is treated as a layer whose characteristics are known.

III - 1 - 2 - 2 - Results

Conditions	Values to compare	Unvented cases						Delta
		External		Internal		Integrated		
		Norm	Present work	Norm	Present work	Norm	Present work	
Reference	Direct-direct transmittance (BDT+BdT)	0,142	0,142	0,142	0,142	0,142	0,142	0
	Total solar energy transmittance (G-value)	0,187	0,210	0,418	0,418	0,311	0,312	0,023
Summer	Direct-direct transmittance (BDT+BdT)	0,142	0,142	0,142	0,142	0,142	0,142	0
	Total solar energy transmittance (G)	0,204	0,227	0,429	0,427	0,332	0,330	0,023

Table 3 : CoDyBa results compared to results given by the norm 13363-2 for different blinds

Reference results are presented in [13363] p. 24.

III - 2 - CAMPBELL & WHITTLE

These results come from the PhD thesis of Neil Campbell.

III - 2 - 1 - Data

These results concern a double glazing with two different integrated blinds. They are given by Campbell & al. and are obtained by a method of ray-tracing. The data of the window are as follows :

Glass				
Case	**Glass Data**		**Values**	**Notes**
Glass	absorption	α	0,07 (--)	From [CAMP1] Fig. 5
	reflection	ρ	0,08 (--)	From [CAMP1] Fig. 5
	transmission	τ	0,85 (--)	From [CAMP1] Fig. 5
	emissivity	ε	no importance	
	conductivity	λ	no importance	
	width	--	6 mm	[CAMP1] p. 5
Blind				
Case	**Slat Data**		**Values**	**Notes**
"White diffuse"	absorption	α	0,1 (--)	[CAMP1] p. 5
	reflection	ρ	0,9 (--)	[CAMP1] p. 5
	transmission	τ	0 (--)	[CAMP1] p. 5
	emissivity	ε	no importance	
	width	W	80 mm	[CAMP1] p. 5
	spacing	P	70 mm	[CAMP1] p. 5
	form	--	flat	[CAMP1] p. 5
"Black diffuse"	absorption	α	0,9 (--)	[CAMP1] p. 5
	reflection	ρ	0,1 (--)	[CAMP1] p. 5
	transmission	τ	0 (--)	[CAMP1] p. 5
	emissivity	ε	no importance	
	width	W	80 mm	[CAMP1] p. 5
	spacing	P	70 mm	[CAMP1] p. 5
	form	--	flat	[CAMP1] p. 5
Window				
Case	**Window Data**		**Values**	**Notes**
All cases	Layers		6 mm glass - 5 mm air space - blind - 5 mm air space - 6 mm glass	air space thickness equal 10 mm, [CAMP1] p. 5
	Ext. th. ex. c.	h_e	no importance	
	Int. th. ex. c.	h_i	no importance	

Table 4 : Campbell & al. data summary for two integrated blinds

III - 2 - 2 - Results

Fig. R2a : direct-direct transmittance (BDT), for slats at 45°

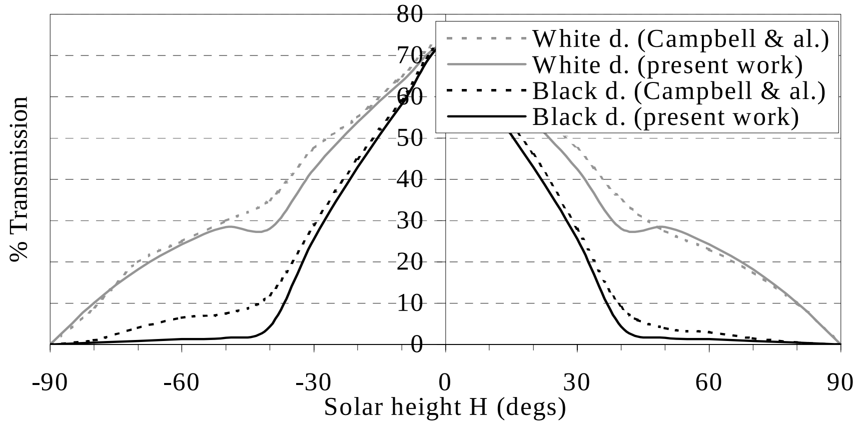


Fig. R2b : direct-direct transmittance (BDT), for slats at 45°

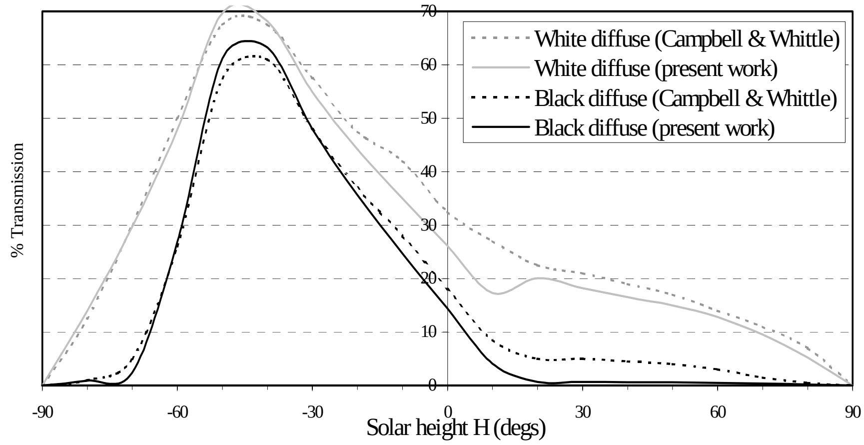


Fig. R2c : direct absorptance (BDA), for slats at 0°

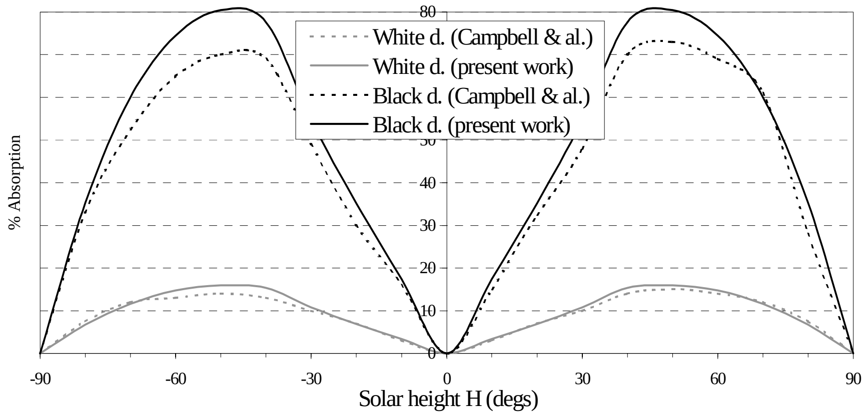
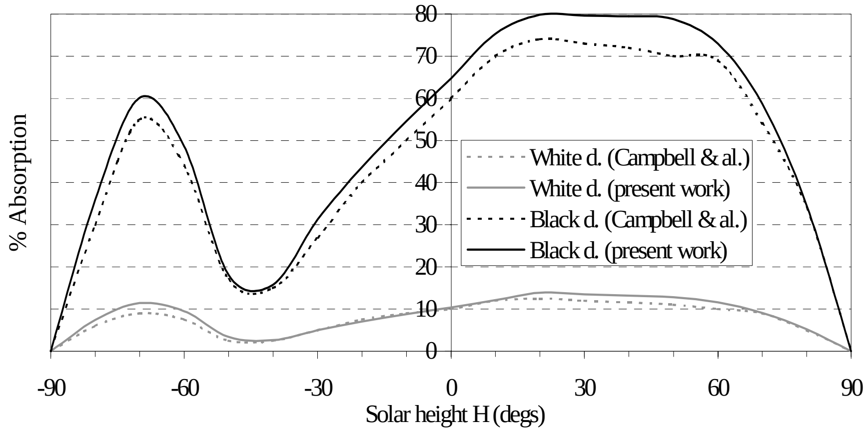


Fig. R2d : direct absorptance (BDA), for slats at 45°



III - 3 - KUHN - BULHER - PLATZER

III - 3 - 1 - Data

The method used by Kühn & al. to determine the optical properties of the slats is a ray-tracing method.

Case			Values	Notes
Glass				
Case	**Glass Data**		**Values**	**Notes**
Glass	absorption	α	0,08 (--)	missing data, completed
	reflection	ρ	0,16 (--)	missing data, completed
	transmission	τ	0,76 (--)	missing data, completed
	emissivity	ε	0,9 or 0,15 (internal coating)	missing data, completed
	conductivity	λ	1,15 W/m.K	missing data, completed
	width	--	6 mm	[KUHN] p. 66
Blind				
Case	**Slat Data**		**Values**	**Notes**
External venetian blind with metallic, light grey slats	absorption	α	0,60 (--)	missing data, completed
	reflection	ρ	0,40 (--)	missing data, completed
	transmission	τ	0 (--)	
	emissivity	ε	0,9 (--)	missing data, completed
	width	W	80 mm	[KUHN] p. 64
	spacing	P	72 mm	[KUHN] p. 64
	form	--	Roll-formed convex slats convex (edges curved downwards)	[KUHN] p. 64
Internal venetian blind with perf. white slats	absorption	α	0,285 (--)	missing data, completed
	reflection	ρ	0,725 (--)	missing data, completed
	transmission	τ	0,05 (perforation ratio = 7,7 %*(25-8)/25)	completed from perf. (1)
	emissivity	ε	0,9 (--)	missing data, completed
	width	W	25 mm	[KUHN] p. 64
	spacing	P	20 mm	[KUHN] p. 64
	form	--	Convex perforated slats (edges curved upwards)	[KUHN] p. 64
Internal 'daylighting' venetian blind	absorption	α	0,57 (lower face) / 0,00 (upper face)	missing data, completed (2)
	reflection	ρ	0,38 (lower face) / 0,95 (upper face)	
	transmission	τ	0,05 (perforation ratio = 7.7 %*(25-8)/25)	completed from perf. (1)
	emissivity	ε	0,9 (--)	missing data, completed
	width	W	25 mm	[KUHN] p. 65
	spacing	P	20 mm	[KUHN] p. 65
	form	--	Concave perforated slats (edges curved upwards)	[KUHN] p. 65
Window				
Case	**Window Data**		**Values**	**Notes**
All cases	Layers		6 mm glass - 16 mm argon space - 6 mm glass	[KUHN] p. 66
	Ext. th. ex. c.	h_e	18,9 W/m².K	[KUHN] p. 63 (18,9 + 0,9*5 = 23,4)
	Int. th. ex. c.	h_i	8 W/m².K	
	U-value	U	1,5 W/m².K	[KUHN] p. 66
	G-value	G	0,67	[KUHN] p. 66

Table 5 : Kühn & al. data summary for three different blinds

(1) 'Perforated' means that there are many small holes in the slat. The transmittance of the perforated area was 7.7%.

(2) For the "internal 'daylighting' venetian blind", the slats are concave and the upper side is coated with a mirror foil, while the lower side is painted matt light grey.

In the next paragraph, results will be compared to some results obtained by the software WIS. WIS is developed at the Fraunhofer Institute for Solar Energy Systems (ISE). It uses a radiosity method (with the assumption of uncurved slats).

III - 3 - 2 - Results

III - 3 - 2 - 1 - Results of optical properties

Fig R3a : direct-direct transmittance (BDT), for case 1 (external venetian blind with metallic, light grey slats), solar azimuth at 0°, slats at 45° (see [KUHN], fig. 8).

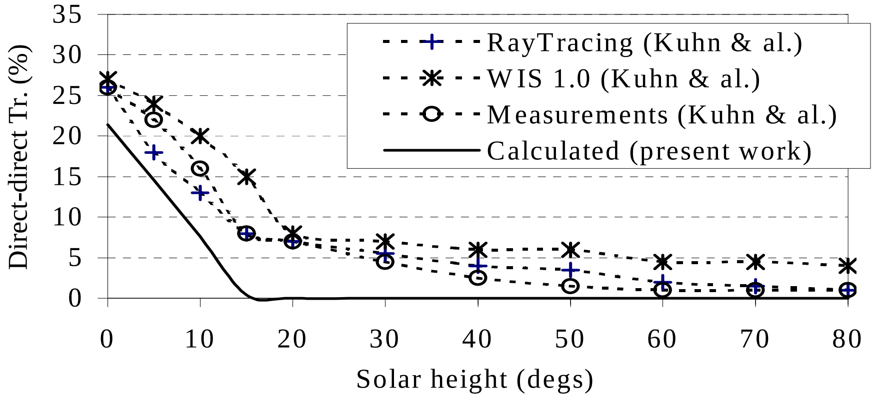


Fig R3b : direct-hemispherical transmittance (BDT+BdT), for case 1 (external venetian blind with metallic, light grey slats), solar azimuth at 0°, slats at 0° (see [KUHN], fig. 9).

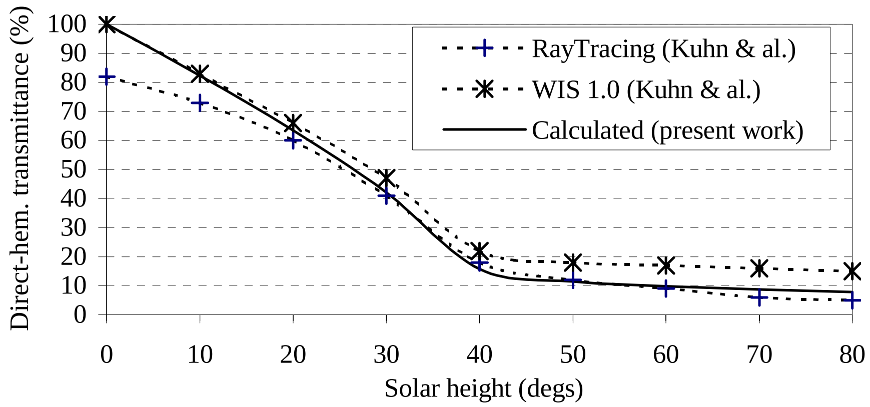


Fig. R3c : direct-hemispherical transmittance (BDT+BdT), for case 2 (internal venetian blind with perforated white slats), solar azimuth at 0°, slats at 0° (see [KUHN], fig. 10).

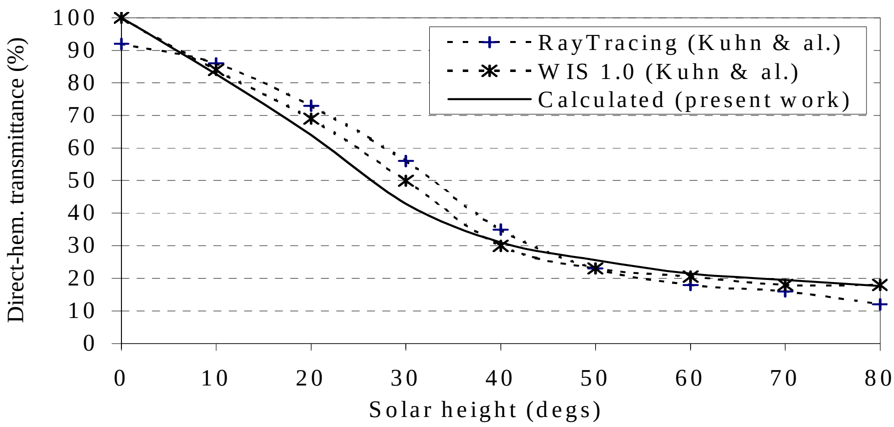


Fig. R3d : direct-hemispherical transmittance (BDT+BdT) for case 3 (internal 'daylighting' venetian blind), solar azimuth at 0°, slats at 45° (see [KUHN], fig. 11).

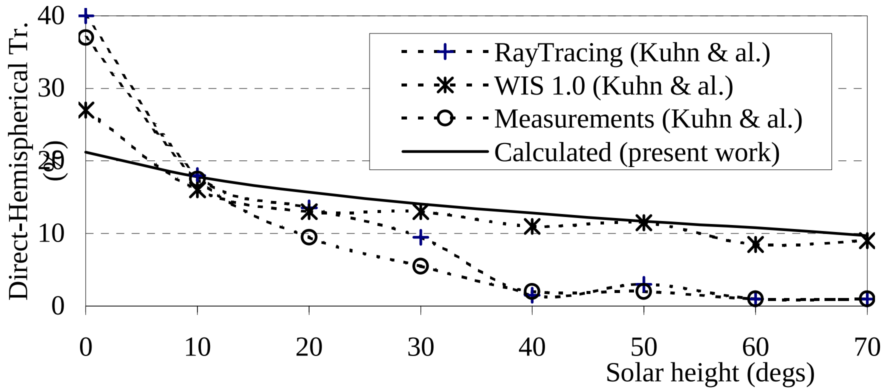
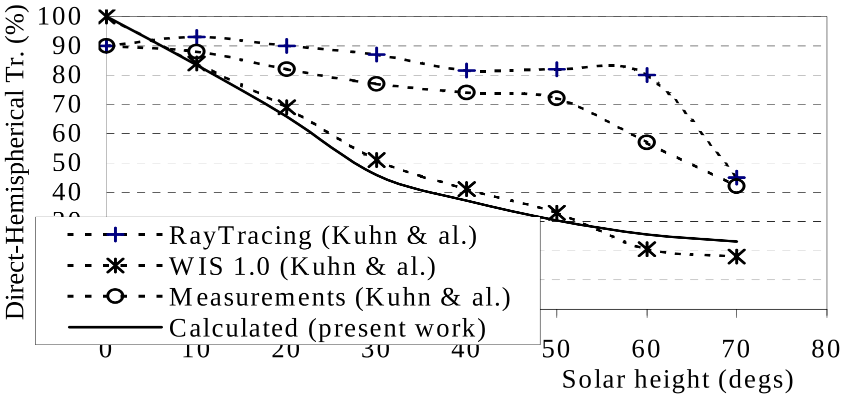


Fig. R3e : direct-hemispherical transmittance (BDT+BdT) for case 3 (internal 'daylighting' venetian blind), solar azimuth at 0°, slats at 0° (see [KUHN], fig. 12).



III - 3 - 2 - 2 - Results of thermal properties (G-values)

Case	H	A	Slat angle	KUHN		Present work		Delta
				G-value calorimetrically measured	calculated g	Not perf.	Perf.	
1	0	0	closed (73°)	0,02 +/- 0,02	0,05	0,024	---	0,004
	0	45	closed (73°)	0,03 +/- 0,02	0,05	0,024	---	0,006
	0	60	closed (73°)	0,03 +/- 0,03	0,05	0,024	---	0,026
	45	0	0	0,09 +/- 0,02	0,13	0,106	---	0,024
	60	0	0	0,04 +/- 0,02	0,08	0,089	---	0,009
	60	0	closed (73°)	0,01 +/- 0,02	0,04	0,024	---	0,004
2	0	0	63	0,42 +/- 0,04	0,41	*0,396*	0,403	0,017
	0	45	63	0,41 +/- 0,04	0,40	*0,424*	0,428	0,018
	0	60	63	0,36 +/- 0,04	0,38	*0,398*	0,40	0,04
	0	0	closed (79°)	0,34 +/- 0,04	0,35	*0,335*	0,351	0,011
	45	0	0	0,50 +/- 0,05	0,47	*0,497*	0,495	0,005
	60	0	0	0,43 +/- 0,04	0,42	*0,421*	0,42	0,01
	60	0	closed (79°)	0,32 +/- 0,03	0,33	*0,279*	0,295	**0,025**
3	0	0	63	0,34 +/- 0,05	0,39	*0,291*	0,303	0,037
	0	45	63	0,38 +/- 0,05	0,39	*0,341*	0,348	0,032
	0	60	63	0,39 +/- 0,05	0,37	*0,345*	0,347	0,043
	0	0	closed (77°)	0,35 +/- 0,05	0,29	*0,195*	0,219	0,131
	45	0	0	0,60 +/- 0,06	0,62	*0,475*	0,473	0,127
	60	0	0	0,56 +/- 0,06	0,57	*0,394*	0,395	**0,165**
	0	0	closed (77°)	0,30 +/- 0,04	0,29	*0,143*	0,169	0,131

Table 6 : Kühn & al. data summary for three different blinds

For "closed (73°)", the blind angle is taken at 73°, by considering that it is closed (the same for 77° and 79°). Notice that the taking into account of the perforation gives better results (closer to Kühn results).

One can notice a good agreement of the results obtained within the framework of this work with those obtained by Kühn & al., except for the case n° 3 which treats reflecting slats. For this case, the radiosity method gives poor results.

III - 3 - 3 - Remarks

Kühn & al. note that the radiosity method for not curved and not perforated slats can be used with a less precision for slats curved and perforated ([KUHN] p. 65). The precision is less in particular if the rays are parallel with the slats. Kuhn notes that surfaces "mirror" are not very well treated by the radiosity method: the ray-tracing is better in this case.

Kühn & al. concluded that radiosity methods for flat (uncurved) and unperforated slats can be used with reduced accuracy for products with curved and colored slats with or without perforation. They remark that products with mirror-finished surfaces cannot be described accurately using radiosity methods, while the ray-tracing method is applicable to all products and allows a precise calculation of the solar transmittance.

III - 4 - LUND

III - 4 - 1 - Data

Two venetian blinds, "White slat 28/22" and "Blue slat 28/22", are used for the measurements.

The measurements were performed in a well-insulated box, placed in a room at about 20 °C. The box had a double glazing unit that was in contact with the sun and the outdoor climate through a window in the south wall ([LUND] p. 15).

Glass				
Case	**Glass Data**		**Values**	**Notes**
Glass	absorption	α	0,07 (--)	missing data, completed
	reflection	ρ	0,08 (--)	missing data, completed
	transmission	τ	0,85 (--)	missing data, completed
	emissivity	ε	0,9 (--)	
	conductivity	λ	1,15 W/m.K	missing data, completed
	width	--	4 mm	[LUND] p. 15
Blind				
Case	**Slat Data**		**Values**	**Notes**
"White slat 28/22"	absorption	α	0,67 (--)	[LUND] p. 112
	reflection	ρ	0,33 (--)	
	transmission	τ	0 (--)	
	emissivity	ε	0,9 (--)	
	width	W	28 mm	
	spacing	P	22 mm	
	form	--	flat	missing data, completed
"Blue slat 28/22"	absorption	α	0,19 (--)	[LUND] p. 112
	reflection	ρ	0,81 (--)	
	transmission	τ	0 (--)	
	emissivity	ε	0,9 (--)	
	width	W	28 mm	
	spacing	P	22 mm	
	form	--	flat	missing data, completed
Window				
Case	**Window Data**		**Values**	**Notes**
All cases	Layers		4 mm glass - 15 mm air - blind - 15 mm air - 4 mm glass	Interpane air space of 30 mm, [LUND] p. 95
	Ext. th. ex. c.	h_e	8 W/m².K	Summer conditions [LUND] p. 76
	Int. th. ex. c.	h_i	2,5 W/m².K	
	U-value	U	2,4 W/m².K	
	G-value	G	0,769 (--)	G_window

Table 7 : LUND data summary for two different blinds

The authors indicates that the G-value is most important for cooling loads, so therefore it is calculated according to the summer case (see [TC163]).

The values of G_sunhade are displayed for different values of solar height. G_sunshade is the ratio :

$$G_{sunshade} = \frac{G_{system}}{G_{window}} \qquad \text{(Eq. 13)}$$

G_system denotes the total solar transmittance of the system formed by the window associated to the venetian blind. G_window represent the total solar transmittance of the window (see [LUND] p. 17).

The measured values of convective heat transfer coefficient were 8/12 and (see discussion [LUND] p. 35).

Note that in PARASOL software, the convective heat transfer coefficients between the outside pane and the ambient air is set to 15 W/m².K ([LUND] p. 71).

III - 4 - 2 - Results

Note G_sunshade is the ratio of BG(with blind) on BG(without blind at normal incidence).

Fig. R4a : G_sunshade for product "White slat 28/22", (see [KUHN], fig. 6.13 p. 117).

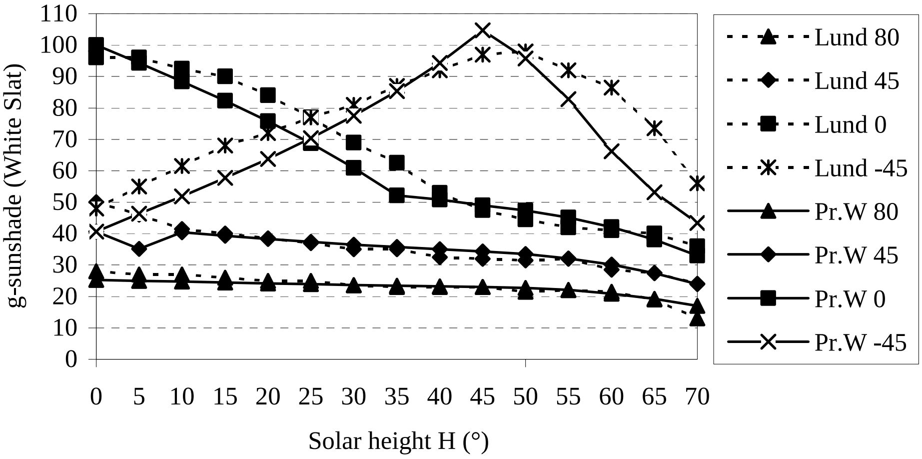
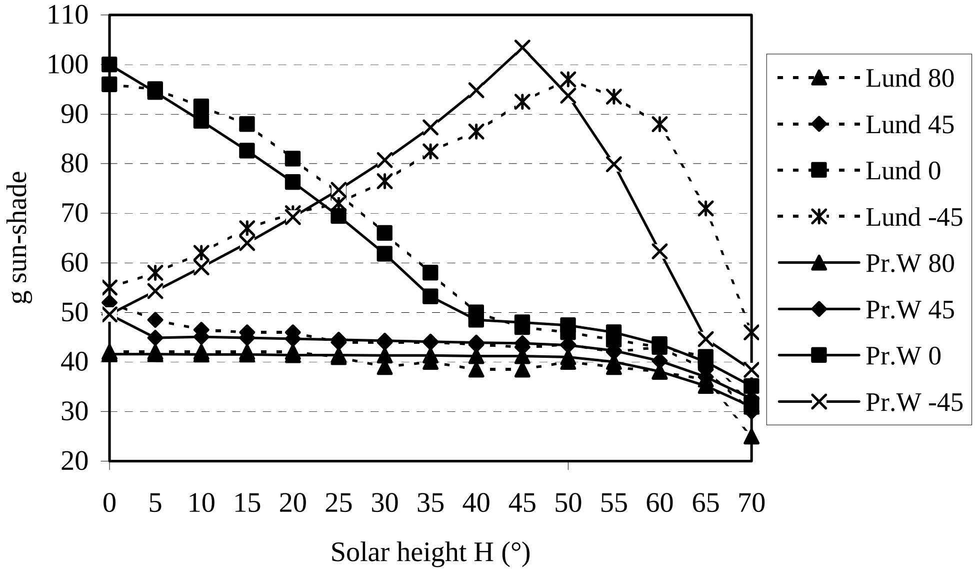


Fig. R4b : G_sunshade for product "Blue slat 28/22", (see [KUHN], fig. 6.17 p. 122).



'Pr. W.' means 'Present Work'.

IV - Conclusions

A window system including an encapsulated venetian blind has been theoretically analysed and practically implemented. The thermal performance of the system has been determined in terms of geometrical parameters, solar height and azimuth, and slat angle.

A validation work has been carried out : we generally found very good agreement. The exceptions concern venetian blinds with mirror-finished surfaces : further work will make it possible to better define the validity field of the thermal cavity.

The present modelling has been implemented in the building simulation software CoDyBa for preliminary tests.

V - References

[TC163] Thermal performance of windows, doors and shading devices - detailed calculations
ISO TC 163 or ISO/DIS 15099

[ZHAO] "Convective heat transfer correlations for fenestration glazing cavities : a review"
Y. ZHAO, D. CURAJA and W. P. GOSS
ASHRAE Transactions, pp. 900-908

[MAZZ] "Encapsulated venetian blind : a new numerical model"
M. MOTTA and L. MAZZARELLA
ISES 1999 Solar World Congress, Jerusalem, Israel, July 4-9 1999

[KUHN] "Evaluation of overheating protection with sun-shading systems"
T. E. KUHN, C. BÜHLER and W. J. PLATZER
Solar Energy Vol. 69, pp. 59-74, 2001

[CAMP1] "Analysing radiation transport through complex fenestration systems"
N. S. CAMPBELL and J. K. WHITTLE
Proceedings of Building Simulation ’97, Volume 1: 173-180.
http://www.ibpsa.org/proceedings/bs97/papers/P069.PDF

[KLEM1] "Calorimetric measurement of the inward-flowing fraction of absorbed solar radiation in venetian blinds"
J. H. KLEMS and G. O. KELLEY
http://eetd.lbl.gov/btp/papers/37038.pdf

[KLEM2] "Solar heat gain coefficient of complex fenestrations with a venetian blind for differing slat tilt angles"
LBLN-39248
Ashrae Transactions 103(1), 1997
J. H. KLEMS and J. L. WARNER
http://eetd.lbl.gov/btp/papers/39248.pdf

[COL1] "Calorimetric measurement of the inward-flowing fraction of absorbed solar radiation in venetian blinds"
M. R. COLLINS and S. J. HARRISON
ASHRAE Transactions, 105(2), pp. 1022, 1999

[COL2] "Sensivity analysis of heat transfer from an irradiated window and horizontal louvered blind assembly"
M. R. COLLINS, S. J. HARRISON, P. H. OOSTHUIZEN and D. NAYLOR
ASHRAE Transactions, pp. 503

[YE] "Convective heat transfer from a window with a venetian blind : detailed modelling"
P. YE, S. J. HARRISON, P. H. OOSTHUIZEN, D. NAYLOR
ASHRAE Transactions, 105(2), pp. 1031-1037

[OOS1] "The effect of heat generation in inclined slats on the natural convective heat transfer from an isothermal heated vertical plate"
P. H. OOSTHUIZEN, L. SUN and D. NAYLOR
http://tetra.mech.ubc.ca/CFD03/papers/paper29PF2.pdf

[FANG] "A study of the U-factor of the window with a high-reflective venetian blind"
X. D. FANG
Solar Energy Vol. 68, No. 2, pp. 207-214, 2000

[ASH93] Fundamental Handbook 1993

[13363] Solar protection devices combined with glazing
Part 2: reference calculation method

[WRI1] "Calculating center-glass performance indices of windows"
J. L. WRIGHT
ASHRAE Transactions (104(1), pp. 1230-1241, 1998

[LUND] "Solar protection in buildings"
M. WALL and H. BÜLOW-HÜBE
Part 2: 2000-2002
Lund Institute of Technology, Lund University, 2003
Report EBD-R--03/1

[MCD1] "A method to define shading devices considering the ideal total solar energy transmittance"
M. C. DUBOIS
Proc. of the Eurosun 2000 Conference, June 19-22, Copenhagen (Denmark)

[MCD2] "A simple chart to design shading devices considering the window solar angle dependent properties"
M. C. DUBOIS
Proc. of the Eurosun 2000 Conference, June 19-22, Copenhagen (Denmark)

[CDB] CODYBA, a design tool for buildings performance simulation
J. Noel, J.-J. Roux, P. S. Schneider
Building Simulation 2001, Rio de Janeiro, Brazil, August 13-15, 2001