Modelling the solar factor of glazing combined with indoor Venetian blinds

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ABSTRACT: Windows and facade systems combining solar control glazing with indoor Venetian blinds can be a very effective strategy to provide thermal and visual comfort. The solar factor of such systems strongly depends on the blind tilt angle and on the relative angular positions of the Sun in respect to the window. In the present paper a modified version of Tilmann E. Kuhn model for the complete angular determination of the solar factor is presented and discussed.
The new version was developed in order to avoid the need for measured angular glazing properties and of calorimetric measurements of the solar factor for the window system, which were data required in the original version. This implementation has been carried out by means of a suitable extension of Arne Roos glazing angular variation model and by using the J.L.J. Roosenfeld's approach for complex systems. Moreover a three spectral band reformulation in place of broadband formulation has been introduced to improve the accuracy of the new version.
An experimental angular characterisation of the solar factor has been carried out on a case study adopting mirror finished blinds. The analysis of the results shows that: in the new fully predictive approach the accuracy improvement of adopting a three-band formulation can be significant; the implemented version still ensures a good agreement with measured values, at least for this case study, with no need of angular data as input.

Keywords: energy efficiency, building, glazing, shading, solar control, daylighting, angular dependency, modelling, calorimetric measurements, ray-tracing

1. INTRODUCTION

Windows and façade systems combining solar control glazing with Venetian blinds can be a very effective system to provide indoor thermal and visual comfort.

The solar factor of such systems strongly depends on the blind tilt angle and on the relative angular positions of the Sun with respect to the window. Therefore a complete angular characterisation plays a fundamental role in the evaluation of effective solar factors of a façade and to prove the effectiveness of a control strategy or new advanced shading devices.

Of course calorimetric point measurements at many angles would be a too expensive procedure to characterise a given product.

A general evaluation method has been recently developed by T.E. Kuhn.[10] and [11]. It is based on raytracing and on an analytic and simplified physical model of the interaction between glazing and shading devices. It requires components optical data at normal incidence and only a couple of calorimetric measurements, which are used to fit two internal parameters related to the glazing angular variation function and to the thermal exchange. It can be used "stand alone" or within building simulation programs

In this paper we present and discuss a modified version of T. E. Kuhn model, which has been implemented in order to completely avoid the need of angular and direct calorimetric measurements.

2. NOMENCLATURE

Angle definitions:

γ_f	façade orientation
γ_s	solar azimuth angle
$\gamma \equiv \gamma_s - \gamma_f$	relative azimuth
α_s	solar altitude angle
α_{in}	angle of incidence
α_p	profile angle
β_n	slat tilt angle

Properties of glazing and blinds:

$A^{(')}_{,b,c,d}$ where,

- A = [τ / ρ / α / g] for [transmittance / reflectance / absorbance / solar factor]
- b = [e / v / e-UV / e-VIS / e-NIR] for [solar / light / solar limited to UV range etc.] spectrum
- c = [dif / nothing] for [diffuse irradiation / otherwise]
- d = [GLZ / SHD / nothing] for [glazing /shading / total]
- (') = if radiation hits the inner surface

The following angle transformations hold:

$$\alpha_{in} = \arccos(\cos\alpha_s \cdot \cos\gamma)$$

$$\alpha_p = arc\tan(\frac{\tan\alpha_s}{\cos\gamma}\cdot)$$

3. MODELS DESCRIPTION

The original formulation of T. E. Kuhn model is described in detail in [10]. Here we report its main conceptual layout and describe the modification developed in order to improve its accuracy and predictive features. All the versions are based on a formulation of the solar factor that combines the angular optical properties of the glazing and of the shading device derived from (or via) distinct characterisations. The approach is shown in Fig.1

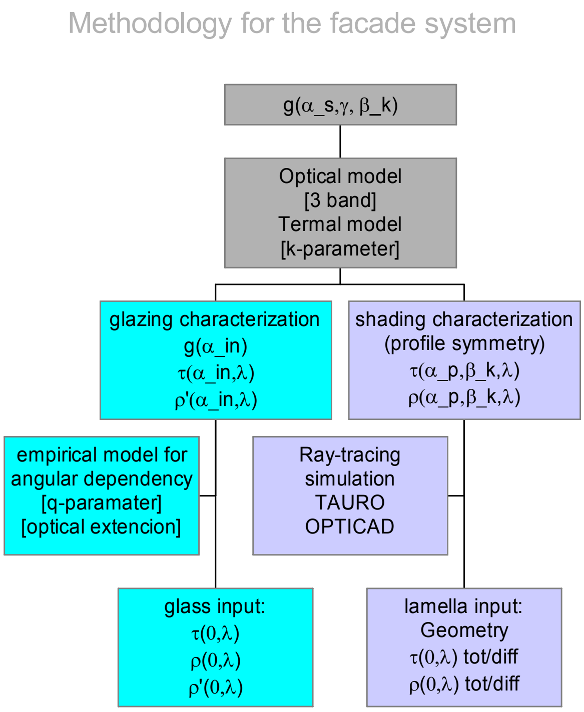

Figure 1 Methodology for modelling the solar factor of a system combining glazing and indoor Venetian blinds.

3.1 Glazing and blinds combination

In the combination of glazing and shading optical properties we have to consider different angular symmetries. Usually for a glazing system, if no special and oriented structures are integrated, we have *incidence angle symmetry*, on the contrary for a Venetian blind without glazing we typically have *profile angle symmetry* (see [1] for angle definitions). For a vertical façade incidence and profile angles coincide when the relative azimuth is null, i.e. only if the radiation and the normal to the surface lay in the same vertical plane.

When we want to extend our modelling to off normal directions - in three dimensions - we may represent both incidence angle and profile angle as functions of the solar altitude and the relative azimuth. So that the complete angular dependency of the *solar factor* can be represented as:

$$g(\alpha_s,\gamma,\beta_k) = g(\alpha_{in}(\alpha_s,\gamma),\alpha_p(\alpha_s,\gamma),\beta_k)$$

To take into account spectral selective properties of glazing and blinds in a simplified way, the original formulation of the model uses a combination of solar and light properties.

In the modified version we have introduced a three band formulation where broad band properties are calculated according to the standard normalised solar spectrum *S(λ)* [3] divided in three part: UV (300nm<λ <380nm), VIS (380<λ <780), NIR (780nm<λ <2500nm)

As example for *e-VIS* transmittance we have:

$$\tau_{e-VIS} = \int_{380nm}^{780nm} S(\lambda)\tau(\lambda)d\lambda$$

$$w_{e-VIS} = \int_{380nm}^{780nm} S(\lambda)d\lambda = 57\%$$

Where w_{e-VIS} is *e-VIS* relative weight in solar energy.

Note that "*e-VIS* integration" differs from standard "*light* integration" since the latter is weighted with eye-sensitivity. In principle only the former has physical meaning in evaluating the solar factor.

The reason for this reformulation is to have a proper evaluation of the energy in the visible range and to improve the accuracy in the broad band context.

It has been proven in [8] that in deriving optical properties of double glass units, the accuracy of this three band approach is very high (relative errors lower then 1% compared to fully spectral calculation). Below we briefly describe the original formulation and the modified version. As original formulation, we refer here to the first formulation presented by Kuhn in [9], which is a generalised and improved version of the formula given in the simplified standard [7].

Solar/light original formulation:

$$g = g_{GLZ}(\alpha_{in}) - g_{II} - g_{III} - g_{IV}$$

$$g_{II} = \frac{\tau_{e,}(\alpha_{in})\cdot\tau_{b,dif,GLZ}\cdot\rho_{b,SHD}(\alpha_p,\beta_k)}{1-\rho'_{b,dif,GLZ}\cdot\rho_{b,dif,SHD}}$$

$$g_{III} = k\cdot\frac{\tau_{e,GLZ}(\alpha_{in})\cdot\alpha'_{b,dif,SHD}\cdot\rho_{b,SHD}(\alpha_p,\beta_k)}{1-\rho'_{b,dif,GLZ}\cdot\rho_{b,dif,SHD}}$$

$$g_{IV} = \frac{\Lambda}{\Lambda_2}\cdot g_{GLZ}(\alpha_{in})\cdot\alpha_{b,SHD}(\alpha_p,\beta_k)$$

$$\Lambda = (\frac{1}{U_{GLZ}}+\frac{1}{\Lambda_2})^{-1} \qquad \Lambda_2 = 18\,W/m^2K$$

Where in case of Heat Mirror glazing *"b"* stands for *"e"* and refers to solar broad band properties, while in case of Solar Control glazing *"b"* stands and for *"v"* and refers to visual (light) broad band properties as in standards.

The terms which are summed to obtain the total solar factor have respectively the following physical meanings:

- I) what reaches the blinds (inside the room)
- II) what is reflected by the blinds to the exterior
- III) what is reflected by the blinds, absorbed by the glazing and transmitted outward
- IV) what is absorbed by the blinds and transmitted to the exterior through the glazing

Three bands reformulation:

$$g = \sum_{b=e-UV,e-VIS,e-NIR} w_b g_b \qquad w_{e-UV} = 3{,}4\% \quad w_{e-VIS} = 57{,}0\% \quad w_{e-NIR} = 39{,}6\%$$

$$g_b = g_{b,GLZ}(\alpha_{in}) - g_{b,II} - g_{b,III} - g_{b,IV}$$

$$g_{b,II} = \frac{\tau_{b,}(\alpha_{in}) \cdot \tau_{b,dif,GLZ} \cdot \rho_{b,SHD}(\alpha_p, \beta_k)}{1 - \rho'_{b,dif,GLZ} \cdot \rho_{b,dif,SHD}}$$

$$g_{b,III} = k \cdot \frac{\tau_{b,GLZ}(\alpha_{in}) \cdot \alpha'_{b,dif,SHD} \cdot \rho_{b,SHD}(\alpha_p, \beta_k)}{1 - \rho'_{b,dif,GLZ} \cdot \rho_{x,dif,SHD}}$$

$$g_{b,IV} = \frac{\Lambda_{int}}{\Lambda_2} \cdot g_{b,GLZ}(\alpha_{in}) \cdot \alpha_{b,SHD}(\alpha_p, \beta_k)$$

The *k parameter*, which appears in the third term of both formulations, in the former formulation is deduced by fitting the results from the model with a direct calorimeter measurement. In the new formulation the need for the calorimetric measurement has been removed by introducing an expression for *k*. In analogy with the last term the thermal problem can be considered equivalent to the following thermal network:

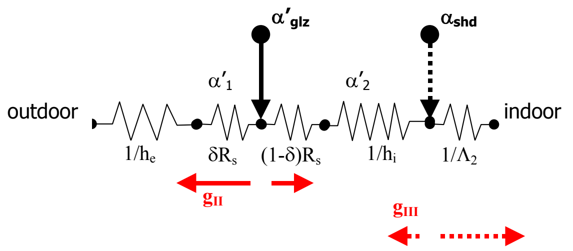

Figure 2: Equivalent thermal network for modelling heat transfer due to radiation absorbed by the glazing (after reflection on the blinds) and by the blinds.

So that *k* is given by:

$$k = \Lambda \cdot ((1-\delta) \cdot R_s + \frac{1}{h_i} + \frac{1}{\Lambda_2})$$

$$R_s = \frac{1}{U_{GLZ}} - \frac{1}{h_i} - \frac{1}{h_e}$$

where R_s is the thermal resistance between the inner and outer glazing surfaces and δ gives the fraction of the glazing thermal resistance from the position in which the absorption occurs and the external surface. If δ is null all the secondary absorption is at the external surface while for $\delta = 1$ it is absorbed at the indoor surface.

According to Rosenfeld approach [2] for a general complex glazing, δ can be derived as:

$$\delta = \int_0^1 r_s(x) a(x) dx$$

where: $0 \le x \le 1$ is the normalised distance of absorption from the external surface ($x=0$) of the glazing; $a(x)dx = \alpha'(x)dx/\alpha'$ is the normalised back absorption in the infinitesimal layer of thickness dx; $r_s(x) = R_s(x)/R_s$ is the normalised thermal resistance between the external surface and point x.

Since in double glazed units the absorption occurs only close to point 0 and 1 we can approximate:

$$\delta \approx \frac{\alpha_2'}{\alpha'} \approx \frac{\alpha'_{s,2}(0)}{\alpha'_s(0)}$$

For simplicity, we have made a further approximation by taking the values of solar absorbance of internal pane and of double glazing at normal incidence.

3.2 Glazing characterization

To derive angular properties of glazing from normal incidence values, which are typically the only available with commercial products, we may use the model of A. Roos [5]. It gives empirical expressions of the solar factor as a function of a parameter *q* , whose values are associated each to a certain group of glazing coating typologies.

In the original characterization (as input for solar/light formulation) an additional experimental characterization at 60° was produced to fit the *q parameter* in the angular variation function.

This requires the measurement of up to six spectral optical properties for each coated glass, i.e. : transmittance and front and back reflectance for both polarisation modes at 60°.

A discussion on the magnitude of errors due to unpolarised angular characterisation is given in [8].

The use of the Roos model to predict the angular dependency of the solar factor allows to avoid the need for the above mentioned angular measurements. Its accuracy has already been proven in [6] and was confirmed in further experimental studies [8]. One important exception has been found in [10] for glazing with selective coating on low-iron substrates. Roos model has the limitation that in principle it only applies to the solar factor so that, for the purpose of our modelling, we propose a suitable extension to optical properties by making the following assumptions:

- all spectral and broad band transmittances have the same angular dependency
- the above functional dependency is the same angular dependency of the solar factor according to Roos model,
- absorption is constant until 75° and then drops linearly to zero at 90°

The last assumption is intended only for solar control and heat mirror glazing and finds confirmation in recent works of A. Roos and A. Werner [9].

In formulas we have:

$$g(\alpha_{in}) = f_{p,q}(\alpha_{in}) \cdot g(0°)$$
$$\tau(\alpha_{in}) = f_{p,q}(\alpha_{in}) \cdot \tau(0°)$$
$$\alpha(\alpha_{in}) = \begin{cases} \alpha(0°) & \alpha_{in} \le 75° \\ \alpha(0°) \cdot (\frac{90° - \alpha_{in}}{15°}) & \alpha_{in} > 75° \end{cases}$$

where Ross empirical function is given by

$$f_{p,q}(z = \frac{\alpha_{in}}{90°}) = 1 - az^l - bz^m - cz^n$$
$$a = 8 \qquad l = (5.2 + 0.7q)$$
$$b = 0.25/q \qquad m = 2$$
$$c = (1 - a - b) \qquad n = (5.26 + 0.06p) + (0.73 + 0.04p) \cdot q$$

where *p* is the number of panes and *q* depends on the coating typologies [5].

For instance *q=4* for clear float glass, *q=2.5* for single silver coated pane (low-e) and *q=1* for double silver coatings (highly selective).

3.3 Shading characterisation

Different characterisation methods can be used for deriving the angular optical properties of the shading device which are required in both formulations. We have used TAURO, a ray-tracing tool based on OPTICAD and developed by Fraunhofer ISE. Its accuracy has been validated in [4]

The input data are lamella's optical and geometric properties: broad band (*solar/light* or *e-UV*, *e-VIS* and *e-NIR*), total and diffuse reflectance on upper and rear surfaces, thickness, width, distances, and curvature.

The output values are angular (function of profile angle) broad band transmittance and reflectance of the Venetian blinds system, considered as an equivalent vertical pane

To derive diffuse properties from directional to hemispherical values for both glazing and shading systems the coefficients in Tab.1 have been used, respectively for rotational (glazing) and translational (blinds) symmetries. A derivation is given in [8].

$$A_{dif,GLZ} = \sum_i a_i \cdot A_{dif,GLZ}(\alpha_{in,i})$$
$$A_{dif,SHD} = \sum_j b_j \cdot A_{dif,SHD}(\alpha_{p,j})$$

Table 1: Angular weight coefficients for the determination of diffuse properties of devices having symmetry with respect to incidence angle (a_i) or profile angle (b_j)

$\alpha_{in,i}$	a_i	$\alpha_{p,j}$	b_j
0°	0.017	0°	0.130
15°	0.129	±15°	0.126
30°	0.224	±30°	0.113
45°	0.259	±45°	0.092
60°	0.224	±60°	0.065
75°	0.129	±75°	0.034
90°	0.017	±90°	0.005

4. MODEL VALIDATION

4.1 Description of the case study

The façade system used to validate the predictive features of the new version and to compare it with the performance of the original model is composed by a Solar control double glazing and an indoor Venetian blind designed for daylighting applications. Other systems are assessed in [11].

The external pane is a glass with spectrally selective and low emissive double silver coating facing the cavity, which is of 16mmm and filled with Argon gas. The internal pane is clear float glass.

The lamellas are 50mm wide, mirror finished on the upper surface, concave with 29mm apart.

Glazing *U value* is *1.12 W/(m²K)* and *g=0.307*.

Broad band optical properties at normal incidence for glazing and the lamellas are reported in Tabs.2&3.

Table 2: Glazing broad band optical properties at normal incidence

	τ(0°)	ρ(0°)	ρ'(0°)
e (solar)	0.273	0.262	0,366
v (light)	0.541	0.137	0.171
e-UV	0.074	0.120	0.150
e-VIS	0.445	0.160	0.205
e-NIR	0.042	0.423	0.616

Table 3: Lamella broad band diffuse and total reflectance

	ρ tot	ρ' tot,	ρ dif,	ρ' dif
e (solar)	0.855	0.279	0.032	0.268
v (light)	0.848	0.304	0.030	0.295
e-UV	0.672	0.074	0.052	0.065
e-VIS	0.839	0.287	0.030	0.278
e-NIR	0.894	0.285	0.033	0.272

4.2 Use of the empirical model extension

While making the extension of Roos model to optical properties we use *q=1* for the glazing (with double silver coating), according to Roos coating categories, [5]. The results derived from the extended model have been compared with experimental values at 60° incidence in Tab.4. and show a good agreement, with relative errors around 5%.

Table 4: Glazing angular optical properties, empirical model extension versus experimental values

	τ(60°)		ρ'(60°)	
	exp.	**model**	**exp.**	**model**
e	0.193	0.202	0.428	0.441
v	0.412	0.406	0.288	0.302
e-UV	0.032	0.044	0.159	0.159
e-VIS	0.314	0.330	0.328	0.306
e-NIR	0.030	0.032	0.597	0.623

4.3 Calorimetric measurement

In Tab.5 we report the results of the direct measurements of the solar factor for the considered facade system. Measurements have been performed for different tilt angles of the blinds and different incidence angles of solar radiation in the laboratories of Fraunhofer ISE using the Solar Simulator and the Calorimetric Apparatus.

4.4 Models comparison

In the Figs.3-6 and Tab.6 the results of both the original (O.M.) and the modified (R.M.) versions of the model and of the calorimetric measurements (C.M.) have been plotted.

The values assigned to parameters *q* and *k* are:

- O.M.: *q=1* (best fit) and *k = 0.4* (best fit)
- R.M.: *q=1* (from Roos categories) and *k = 0.68* (from formulas in section 3)

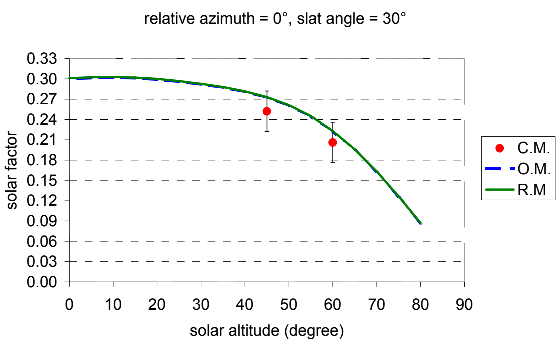

Figure 3 Original (O.M.) and reformulated model (R.M.) versus Calorimetric Measurements (C.M.)

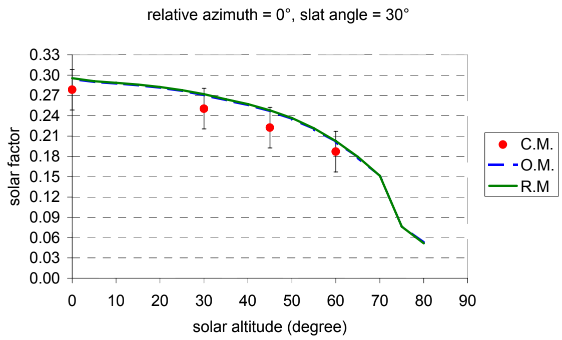

Figure 4 Original (O.M.) and reformulated model (R.M.) versus Calorimetric Measurements (C.M.)

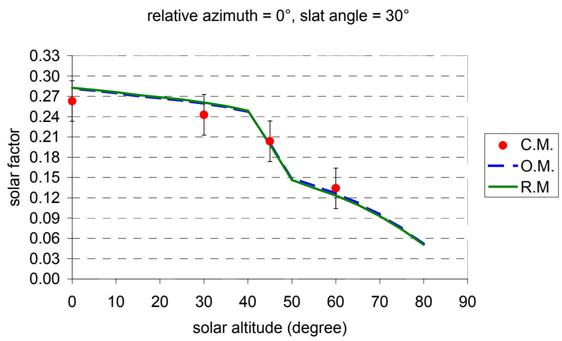

Figure 5 Original (O.M.) and reformulated model (R.M.) versus Calorimetric Measurements (C.M.)

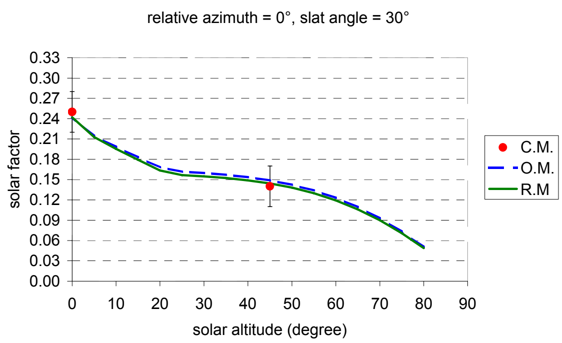

Figure 6 Original (O.M.) and reformulated model (R.M.) versus Calorimetric Measurements (C.M).

Table 5: Direct calorimetric measurement of the angular solar factor of the facade system under study

α_s	γ	β_n	α_{in}	α_p	g
45°	0°	0°±5°	45°	45°	0.25±0.03
60°	0°	0°±5°	60°	60°	0.21±0.03
0°	0°	30°±5°	0°	0°	0.28±0.03
30°	0°	30°±5°	30°	30°	0.25±0.03
45°	0°	30°±5°	45°	45°	0.22±0.03
60°	0°	30°±5°	60°	60°	0.19±0.03
30°	45°	30°±5°	52°	39°	0.21±0.03
45°	45°	30°±5°	60°	55°	0.18±0.03
0°	0°	45°±5°	0°	0°	0.26±0.03
30°	0°	45°±5°	30°	30°	0.24±0.03
45°	0°	45°±5°	45°	45°	0.20±0.03
60°	0°	45°±5°	60°	60°	0.13±0.03
30°	45°	45°±5°	52°	39°	0.21±0.03
0°	0°	65°±5°	0°	0°	0.25±0.03
45°	0°	65°±5°	45°	45°	0.14±0.03

Table 6: prediction of the original and the modified model at 45° relative azimuth.

α_s	β_n	g O.M.	g R.M.
30°	30°±5°	0.237	0.239
45°	30°±5°	0.203	0.204
60°	30°±5°	0.151	0.152
30°	45°±5°	0.230	0.231
45°	45°±5°	0.128	0.124
60°	45°±5°	0.100	0.093

The two models provide almost coincident predictions even if they differ in terms of evaluation of the *parameter k* and in term of spectral band formulation. This proves that the more detailed modelling of the spectral and thermal interaction between blinds and glazing, which has leaded to *three band* formulation and to a formula for *k*, may achieve the same accuracy of the previous formulation, which needs a calorimetric input to derive a value for *k*.

We expected that the way in which *solar/light* formulation takes into account the radiation that is reflected by the binds (II term in the formula for the total solar factor) produces systematic underestimation of the total solar factor. This is because the use of light transmittance is based on the approximation that glazing spectral selectivity has already filtered out the incoming NIR radiation. But light transmittance $\tau_{v,GLZ}$ is typically larger than solar direct transmittance in the visual range, $\tau_{eVIS,GLZ}$, and NIR radiation is not completely filtered.

This finds a confirmation in the lower value of *k* (in the III term), which creates a compensation of the previous effect and balances the result.

We also note that both formulations using TAURO shading characterisation predict a "cut off" (i.e a steep decrease as a function of the solar altitude) when

$$\alpha_p \approx 90° - \beta_k$$

Around the "cut off" position the results of the models are very sensitive to the slat angle. This fact, together with the intrinsic deviation of the slat angle recommend to be very careful when comparing model predictions with measurements for positions close to the cut off angle.

We finally observe that, considering the experimental errors bars, all the modelled results show agreement with the calorimetric measurements.

4.5 Sensitivity analysis

We have already confirmed that *q=1* as predicted by Roos works very well for the glazing under study. A variation of the *q parameter* from *1* to *4* has been considered to show possible effect of an non accurate estimation of *q*

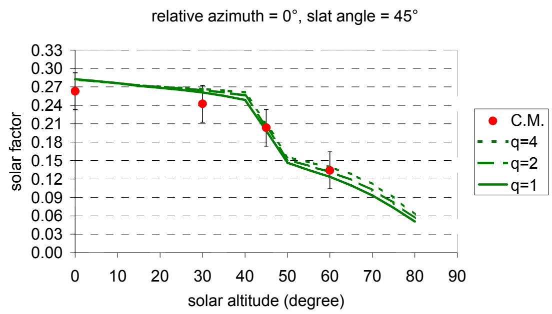

Figure 7: q-parameter sensitivity in three band formulation

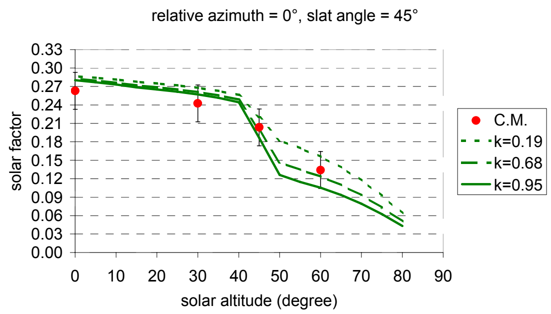

Figure 8: k-parameter sensitivity in three band formulation

In Fig.7 we see that the choice of *q* can affect the prediction of the solar factor of about one deviation with respect to measured values error bars. This happens of course at large incidence angles and with blinds relatively opened, i.e. before the cut off. In fact after the cut off the effect of glazing angular dependency is less important.

In the same way in Fig.8 we show the influence of *k parameter*. Its physical range of values and its expected value *k=0.68* are derived according to the definition and given in the modified version.

5. CONCLUSION

A fully predictive reformulation of the model introduced in [10] to derive the solar factor of a window system including internal Venetian blinds has been developed. It has been validated for one façade system.

It reduces the need of input data to spectral properties at normal incidence for the glazing and the lamella. The improved predictive features are based on the empirical model categories [5] and on the modelling of the secondary heat transfer due to radiation absorbed by the glazing in presence of internal blinds. In this context an extension of the empirical model has been introduced to derive the angular dependency of the back reflectance.

An experimental angular characterisation of the solar factor has been carried out on a case study adopting mirror finished blinds. The analysis of the results shows that: in the new fully predictive approach the accuracy improvement of adopting three-band formulation can be significant; the implemented version still ensures a good agreement with measured values, at least for this case study, with no need of angular data for the glazing as input, for low-iron glazing the accuracy can be lower [10].

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