THE SIMULATION OF GLAZING SYSTEMS IN THE DYNAMIC THERMAL MODEL HTB2

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ABSTRACT

This paper discusses the modification and testing of an existing dynamic thermal model to include the calculation of the effects of glazing and shading options such as slatted blinds. It discusses the selection and development of algorithms, the testing of component sub-models against detailed models, and provides comparisons against theoretical and measured benchmarks. The modified model is found capable of predicting total solar transmission of glazing with mid-pane shading combinations, expressed as a G-value, to ±0.04. Though further refinement may be made, this is considered sufficient to distinguish between many glazing options faced at a design stage.

INTRODUCTION

As building envelopes become better insulated, the performance of glazing systems becomes more critical to the overall performance of a building. The specification of solar control devices, in particular of horizontal or vertical blind systems, would still appear to cause considerable controversy in the design industry in respect to the best options for a particular situation. In many cases internal blinds, often in dark colours, are used by default, with consequences of uncomfortable summer conditions.

In order to allow the designer a knowledgeable choice in solar control, better information is needed, and it is inevitable that much of that information will be generated through modelling; either directly, to inform the designer case by case, or indirectly, through simulation case-studies, guidance, and rules of thumb. Of course, in order to provide useful information, the models used must adequately simulate the significant aspects of glazing. This has been a significant area for research and model development, with a number of differing approaches taken (e.g. Campbell & Whittle, 1997, Maccari & Zinzi, 2001, Andersen et al., 2003, Dijk & Oversloot, 2003).

This paper focuses on modifications to, and the testing of, an existing dynamic thermal simulation code, HTB2 (Alexander, 1997), in order to allow more detailed consideration of glazing and solar shading systems. In particular these changes were required in order to model the effects of the placement and specification of horizontal and vertical blinds.

MODIFICATIONS TO MODEL

The treatment of glazing in HTB2 had remained essentially unchanged from its initial formulation in the late 1980’s. This model was intended as a general-purpose finite difference simulation code for energy and environmental performance of buildings (Lewis & Alexander, 1990). Features key to the modelling of glazing were the separate treatment of surface radiant and convective heat exchange, and the specification, and explicit calculation, of the thermal state of material layers of fabric. Glazing was intended to be treated in a flexible manner. Thermally, glazing was considered as other fabric elements, so heat flow and internal and surface temperatures were explicitly determined. In terms of transparency, optical characteristics (e.g. total transmission and absorption factors) for a glazing type were specified as look-up tables (for instance as illustrated in figure 1) detailed in steps of 10 degrees of incidence angle. Intermediate values were determined by linear interpolation. This approach was chosen over internal calculation (e.g. via an extinction coefficient) in order to allow the description of glazing types not easily defined in that manner. Shading devices were also specified by look-up tables, describing “masks” of the sky in 10 degree segments, in order to determine the blockage of direct and diffuse solar irradiance (Alexander, Ku Hassan & Jones, 1997). The combination of site and individual surface masks and of the glazing characteristic determined the direct and indirect solar gain to the space.

During an investigation into the modelling of highly glazed spaces Pfrommer et al. (1996) developed a more general glazing and shading model, which was able to be used in conjunction with HTB2 (Pfrommer, 1995). As part of the further development of HTB2, this pre-processor code was acquired and evaluated for potential embedding into the core code.

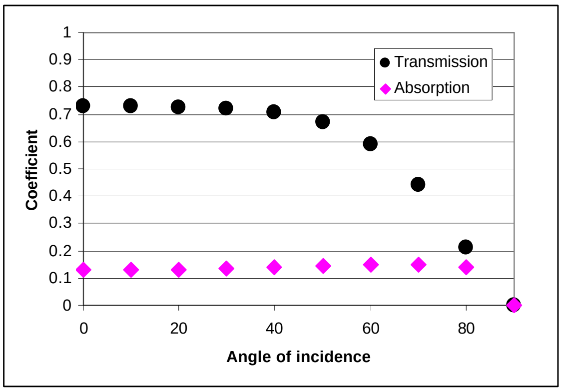

Figure 1; Graphical representation of an original HTB2 glazing characteristic of a 4mm float double glazing unit.

The Pfrommer model, called GLSIM, calculated the transmission characteristics of glass from optical first principles, requiring a specification of glass and film material properties and thickness. Although this approach was shown to be reliable (Pfrommer et al. 1995), in practice the "formula" for most commercial glasses is not readily available to the end user; this made direct embedding problematical, as the necessary input data would not be available. For many commercial glasses however, total transmission characteristics are available; either through published data or through calculation by software such as WIS (Dijk & Oversloot, 2003) or, indeed, the Pfrommer method. In order to retain flexibility in HTB2 it was decided therefore to remain with a tabular input format, and leave the determination of individual layer characteristic external to the software.

The model developed by Pfrommer also included a slatted blind sub-model. This model utilised a view factor calculation approach (similar in scope to that described in ISO 15099:2003) to determine the transmission characteristic of general slatted blinds. In order to allow for the eventual control of slat angle in response to calculated conditions, this sub-model was isolated for embedding within the HTB2 code for explicit, dynamic, calculation of blind layer properties. Also isolated for embedding was the method used for the combination of individual layer characteristics in order to establish total transmission and absorption for the complete glazing system.

In determining solar transmission through elements, the original algorithms of HTB2 operated only from the angle of incidence. As indicated by many researchers (e.g. Klems & Warner, 1997, Janák, 2003) this approach is insufficient to take into consideration asymmetrical optical characteristics such as those produced by slatted blinds. The treatment of optical characteristics was therefore extended to allow the generation of (through the Pfrommer model) and the specification and utilisation of (in the HTB2 code) "2D", or bi-directional, transmission characteristics (e.g. those varying in relative altitude and azimuth). An example transmission characteristic for a horizontal slatted blind system is illustrated in figure 2.

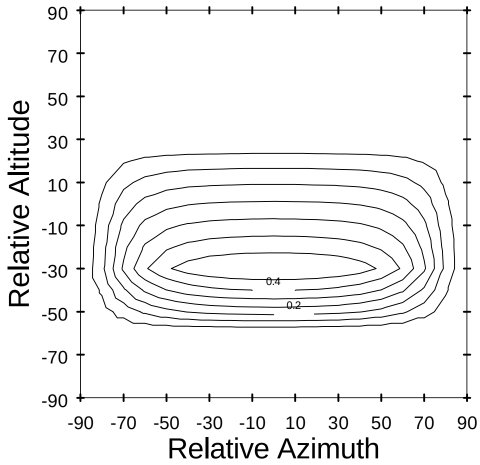

Figure2; Graphical representation of a "2-D" HTB2 glazing transmission characteristic for a double glazing unit of 4mm float glass with horizontal slatted blinds.

Following the original HTB2 methods, 10 degree segments were used to encapsulate the characteristic, with simple linear interpolation used between key points. In addition to Direct-beam transmission ($\tau_{dir-dir}$) and absorption (α), a separate characteristic component for diffuse transmission (e.g. from slat inter-reflections) ($\tau_{dir-dif}$) was introduced. Where previously a global "diffuse transmission" coefficient was required for each glazing type, in the new code diffuse sky and ground transmission is calculated directly through integration of the direct transmission characteristics over the upper (sky) and lower (ground) radiance distributions. In this way, site obstructions and external shading can be explicitly taken into account. The approach can be used to specify horizontal or vertical blind systems without alteration.

The original glazing calculations for HTB2 involved the use of fixed cavity heat transfer resistances, fixed internal heat transfer coefficients, and an isotropic sky radiance model. Following the recommendations of ISO 15099:2003, new cavity and surface heat transfer options were developed. In addition, concerns over the applicability of the simple isotropic sky model to glazing with a highly selective angular sensitivity lead to the adoption of a general anisotropic sky model, developed following Perez (Perez, 1993). In the absence of a better model however, the ground plane remains to be considered as an isotropic hemisphere.

In the thermal treatment of glazing in the modified model, a blind is considered as a thin plane layer (regardless of blade angle). A mid-pane blind thus creates two "half" cavities within the glazing unit, while an external or internal blind will create a new cavity before or after the glazing unit as appropriate. The blind layer may have material properties specified, so that thermal mass and resistance can be taken into consideration. Convective and radiant exchange across the cavities are determined separately. Each cavity can be specified as un-ventilated or ventilated to internal or external spaces. The two cavities do not communicate thermally apart from through the blind material; there is no internal mixing taken into consideration. Further, as HTB2 contains a fundamentally 1-dimensional heat-flow model, the glass, cavity and blind material temperatures are each considered to be uniform across their respective areas.

EVALUATION OF MODEL

In the absence of direct access to measurement facilities, the modifications made to HTB2 were tested against a combination of software standards and previously published laboratory or field trials. WIS 2.0.1 was chosen as the exemplar software, representing a standardised and validated reference model (Dijk & Oversloot, 2003), while detailed test-cell measurement data were acquired through a test programme run by Lund University (Bülow-Hübe, Kvist, & Hellstrom, 2003). The latter data contained hourly total solar transmittance measurements, under real climatic conditions, for a number of slat angles and slat colours. Measurement data for comparison was acquired only for mid-pane configurations of horizontal blind systems, so this paper will concentrate largely on those configurations, as summarised in table 1. In all measurement cases, the blinds were contained between 4mm clear float glass panes in a 30mm cavity. The blind slats were 28mm deep with a 22mm pitch. Slat angle is positive for a downward (e.g. blocking the sky) inclination.

Table 1; Summary of comparison test data configurations

Case	Slat reflectance	Slat Angle °
W0 (white 0°)	0.67	0
W45 (white 45°)	0.67	45
W80 (white 80°)	0.67	80
B0 (white 0°)	0.19	0
B80 (white 80°)	0.19	80

Comparison to Reference model

Comparisons were made through evaluation of average (ME) and root-mean-square (RMSE) error between the reference standards and the modified model. Initial evaluations were made of the blind transmission model in isolation, of the blind transmission model in combination with glass panels, and of the total solar transmission (or G-value) of the glazed systems under standard conditions. The reference for each of these was the WIS software.

Considering the slatted blind in isolation, compared to WIS calculations the calculation of direct beam transmission was seen to be exact (as might be expected from a simple geometrical problem). Calculation of the diffusing beam transmission (e.g. $\tau_{dir\text{-}dif}$) was also good but not perfect, with a mean error of -0.002 and a RMSE of 0.007 across the five configurations. There were found to be larger discrepancies in the absorption characteristic factors however, particularly for large slat angles; this component exhibited a RMSE of 0.023. This is seen to indicate a weakness in the view factor calculation, which at time of writing has not been identified and requires further investigation.

In combination with glass panes (the transmission characteristics of which were determined in isolation, using WIS), there is a further deterioration from the ideal. RMSE error in total transmission of the system has now increased to 0.009, and in absorption to 0.035. Again, the treatment of absorption in the combination algorithm requires further investigation. Figure 3 provides an example comparison of the total system transmission characteristic.

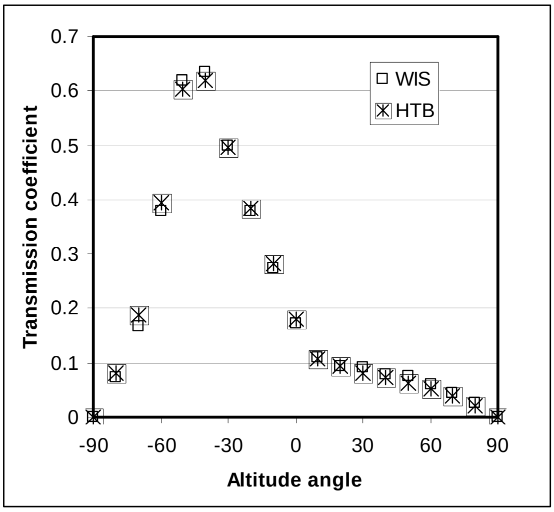

Figure 3; Comparison of total system transmission factor the W45 blind within a double glazed panel

A final comparison against the reference model was made for the prediction, through the whole thermal model, of total solar transmission (G-value) under standard fixed conditions. The G-value was determined in the thermal model through the simulation of a laboratory test cell, using fixed cell temperatures and transfer coefficients on either side of the glazing panel, and irradiating at normal incidence. The boundary conditions for the test were taken from EN 410:1998.

These tests were undertaken for a wider range of blind configuration, and included external and internal placements. A mid-grey blind (reflectance = 0.5) was assumed for all cases. Results of this comparison are shown in table 2. The modified model has been able to predict a standard G-value to within ±0.02 of the reference model.

Table 2; Comparison of G-values as calculated by WIS and by HTB2

Glazing Systems		**Calculated standard G-value**	
Slat angle	**Position**	**WIS**	**HTB2**
20°	Internal	0.66	0.68
	Interpane	0.61	0.63
	External	0.57	0.55
45°	Internal	0.55	0.53
	Interpane	0.43	0.44
	External	0.31	0.32
70°	Internal	0.44	0.40
	Interpane	0.28	0.26
	External	0.11	0.11

Comparison to Measurements

In order to evaluate the performance of the full thermal model, utilising all sub-models and real climatic data, comparison against measured data was considered necessary. The external test cell data acquired from Lund University comprised a quality data set of total solar transmission for a number of configurations, made using a "twin-box" facility (Wall & Bülow-Hübe, 2003). The five measurement cases were each simulated by the modified HTB2 system, "exposing" each glazing system considered, placed on a simple enclosure with constant internal temperature, to the recorded climatic data.

The glazing dynamic hourly g-value, termed g_d in order to differentiate it from the standard laboratory G-value, was estimated from the simulation data as :

$$g_d = \frac{I_g + Q_w - Q'_w}{I_n},$$

where;

I_g is the total radiant solar gain through the glazing (W/m^2),

I_n is the external solar irradiance normal to the glazing (W/m^2),

Q_w is the convective and longwave radiant heat exchange from the internal surface of the glazing (W/m^2), and

Q'_w is the heat exchange from the internal surface of the glazing under identical conditions except with no solar irradiance (W/m^2), achieved through a second simulation.

The authors of the test-cell measurements of total solar transmission indicate their accuracy as better than 5% of the value measured (Bülow-Hübe, Kvist, & Hellstrom, 2003). This seems to be comparable to accuracy's reported by others (e.g. Klems & Warner 1997, Platzer, 2000). Measurements were made on a 10-minute basis. It was noted that, presumably due to varying cloud or wind conditions during a test, the measured values could be seen in some tests to vary rapidly across an hour. Climatic data for simulations was only available in an hourly format, therefore simulation results could only be compared on this time scale. The simulation results would represent the average value over the hour, so the measurement data was averaged to an hourly basis. Any variance over the hour was considered to be a further indication of measurement uncertainty. This typically represented a combined uncertainty in the measured g_d-values of approximately ±0.03.

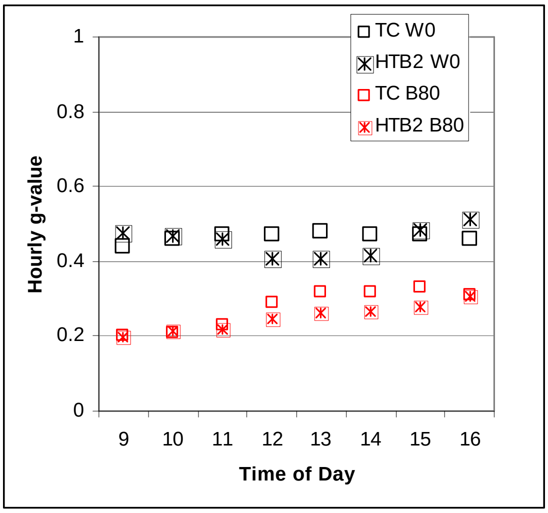

Figure 4; Comparison of hourly system g_d-value for two blind configurations; TC – measured data, HTB2 – simulations

Initial comparisons of the individual hourly results were made with simulations using the original heat transfer algorithms (e.g. using fixed surface heat transfer coefficients, and fixed cavity resistances) of HTB2. Typical results are shown in figure 4. These tests, comprising 36 hours of measurement across the five configurations tested, showed a RMSE of 0.038 in the predictions, with an indication of an overestimate in g_d of +0.02. Figure 5 shows a scattergram of all hourly results, as well as the line of ideal agreement. There is a degree of consistency seen between cases, although there is notable scatter within the both the light and dark 0-degree cases (W0, B0).

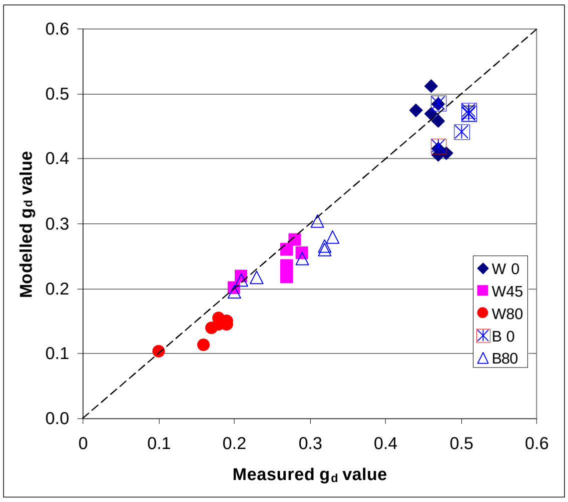

Figure 5; Comparison of all hourly system g_d - values, original model algorithms

Influence of model algorithm

The heat transfer algorithms of the original HTB2 model, as noted, were much simpler than those required by ISO 15099:2003. In response, modifications were made to the cavity resistance algorithms (Cavity) and to the surface convective heat transfer algorithms (Surface), to bring these into line with the standard. Also included was a change to an anisotropic sky radiance model (Sky). The impact of these modifications on the comparisons to the measured data are summarised in table 3.

Table3; Impact of modelling options on the comparison of model to measured data.

Case	ME	RMSE
Original	+0.024	0.038
Cavity	+0.020	0.053
Cavity+Surface	+0.015	0.050
Cavity+Surface+Sky	+0.013	0.037
Cavity+Surface+Sky+5 degree table	-0.005	0.043

It can be seen that the addition of ISO 15099:2003 algorithms appears to reduce the mean bias in the resulting simulations, but notably has had an adverse impact on the overall uncertainty. The final addition of the anisotropic sky model to the simulation improves both the bias and the scatter, and so, as expected, would appear to be necessary to the successful modelling of these slatted blind systems.

As mentioned previously the scatter in the comparison of g_d between the two 0-degree slat angle cases (W0, B0) was of concern. It was noted that during these two measurement cases, the peak solar altitude was just above the cut-off angle for the blind geometry. It was considered that the relatively coarse 10-degree characteristic table format might be affecting those cases.

Therefore further modifications to the model were made to utilise tables specified in steps of five degrees. The results appear in table 3 under the code "5 degree table". This refinement would appear to be useful; the mean error is again reduced and although the RMSE has increased marginally, the scatter about the critical 0-degree slat cases has been reduced significantly, as can be seen in figure 6. As a result the individual configurations now group much more satisfactorily. Little change was found in the cases with the larger blade angles, where solar transmission would be dominated by diffusing and ground based reflections. In those cases the interpolation scheme worked well on the 10 degree tables.

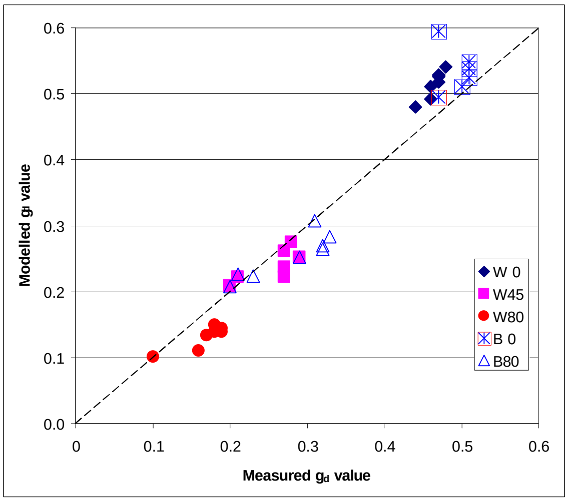

Figure 6; Comparison of all hourly system g_d - values, modified algorithms and 5 degree tables.

DISCUSSION

Although absolute accuracy is often desired, a practical model will be required to make some trade-off between accuracy and usability. Detailed specific software solutions may seek to emulate laboratory cases, but in terms of usability in dynamic modelling, limitations in data requirements and speed of calculation are important considerations. Ultimately, however, a model useful to the design industry must show sufficient accuracy to be able to distinguish between design alternatives.

The RMSE results arising from the comparisons would seem to indicate that the error in the total simulation process is of a similar order to the measurements against which it was being compared. The modifications to HTB2 would appear to be able to calculate, for the glazing types considered, direct, diffuse and re-emitted solar gain coefficients to within ±0.04. In practice this should allow the robust differentiation of glazing design alternatives equivalent to differences in G-value of better than 0.1. Although there is scope for improvement, in particular in the calculation of diffusing effects of blinds, in many applications in the design industry this level of accuracy may be sufficient.

The test cases presented are a case in point. The five configurations of mid-pane blinds that were tested in work reported by Wall & Bülow-Hübe (2003) can be ranked by their average measured g_d value, in order of increasing solar transmission (e.g. assuming a design intent to minimise solar gains). Table 4 compares the rankings made by measurement and made by the modified model in its final configuration. Also indicated in this table are the statistical significance of the difference between a configuration and its next ranked neighbour, as assessed by a t-test on the hourly data for each pair of configurations. Those configurations that are significantly different (to a confidence of 90%) from their next ranked neighbour are marked with an asterisk (*). Thus for instance the measurements distinguished a significant difference in G-value between the W80 and W45 cases, but not between the W45 and B80 cases.

Table4; Rankings of the blind configurations, as indicated by measurement and by simulation.

Configuration	Mean g_d by measurement	Mean g_d by simulation
W80	0.17 (*)	0.13 (*)
W45	0.26	0.24
B80	0.28 (*)	0.26 (*)
W0	0.47 (*)	0.46 (*)
B0	0.50	0.51

The simulations with the modified model were able to match the resolution of the measurements; the rankings are in the same order, and the same pairs are identified as statistically different. This suggests that the modifications to HTB2 will be able to distinguish between basic design alternatives in the choice of blinds.

CONCLUSIONS

Modifications have been made to the dynamic thermal model HTB2 to enable consideration of slatted blind glazing options. These included the development of a data format to enable the specification of optical transmission characteristics in terms of relative altitude and azimuth, the adaptation of algorithms for the calculation of transmission through slatted blinds, and the inclusion of up-to-date standard algorithms for cavity and surface heat transfer. Comparisons to reference standard software and to test-cell measurement indicate that the software could be expected to predict total solar transmission, as expressed as a G-value, to a RMSE of ±0.04. In order to achieve this resolution, it was considered necessary to utilise an anisotropic sky radiance model, and to specify optical characteristics of the blinds to a resolution of 5 degrees. Although there is scope for further improvements in the calculation of absorption characteristic in multi-layer glazing systems, this level of resolution was considered sufficient to distinguish between glazing options to a degree similar to that available from field measurement.

These comparisons were carried out primarily using data for mid-pane blinds within sealed units. The modifications to the software were intended by the authors to be general, in order to allow the specification of internal and external blinds and ventilate cavities. While initial comparisons to other models are promising, further comparisons against measured datasets considering those aspects will ultimately be required to explore fully the general validity of the model.

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