ANALYSING RADIATION TRANSPORT THROUGH COMPLEX FENESTRATION SYSTEMS

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ABSTRACT

This paper briefly reviews recent research into the modelling of complex fenestration systems, before presenting some results obtained by the use of a new (developing) simulation model, utilising Monte Carlo Methods and Geometric Optics (ray tracing). In particular, the distribution of (solar) radiation by windows containing (interstitial) venetian blinds is examined, since they continue to represent conventional window management practice, and radiation transport through them is inherently complex.

These fenestration systems are considered in isolation as a 'single' component, and the material (radiative) properties of the individual blind slats are explored. This would be expensive and/or difficult to achieve using alternative techniques such as full-scale experimental rigs or scale modelling, particularly for thermal data.

INTRODUCTION

While research into advanced glazing technologies (e.g. aerogels; electrochromic windows; holographic materials) continues apace, e.g. IEA Task 18 [**1**,**2**][1], the task of (computer) modelling of window systems/buildings containing these elements becomes increasingly difficult. This is particularly important in 'low-energy' designs and 'green' architecture [**3**,**4**,**5**], which require more detailed information if design failures are to be avoided.

Many existing general thermal and lighting design programs are subject to some of the following 'limitations' :

- they cannot handle truly complex geometry;
- all surfaces are assumed to be grey / Lambertian bodies (perfectly diffuse emitters/reflectors), so that anisotropic material (radiative) properties and spectral (wavelength dependent) variations cannot be handled;
- participating media cannot be modelled (no absorption/scattering/emission);
- no treatment of polarisation, interference or diffraction of radiation (light) is possible.

A number of specialised programs have evolved to investigate the thermal and optical performances of complex fenestration systems, such as WINDOW [**6**, **7**], and the VISION and FRAME programs [**8**] used in conjunction with IEA Task 18. Other models have also been described, e.g. [**9**, **10**].

One-dimensional (1-D) models capable of simulating the spectral angular dependence (including thin-film interference effects from coatings) of complex glazing systems - consisting of parallel elements (i.e. glass and coatings but not blinds) - can also be found [**11**,**12**,**13**].

Computer models based on ray tracing techniques have also offered the potential to relax at least the first three 'limitations', e.g. RADIANCE [**14**] , which has been extensively validated and used to study the performance of blinds, light-shelves and other complex daylighting systems [**15**,**16**]. These are essentially advanced radiation (lighting) models, and cannot provide thermal performance information on their own.

It should be acknowledged that the desire for more sophisticated models is not always shared by potential users. Despite the efforts of organisations such as the IEA, IBPSA, CIBSE and BEPAC, doubts over the validity of results from dynamic thermal simulation programs continue to manifest themselves (e.g. [**17**,**18**]), and the limited use of computer software for lighting design by non-specialists in the UK has been emphasised in two recent surveys [**19**, **20**].

THE 'IMPORTANCE' OF BLINDS

One might pose the question, "...why study venetian blinds at all ?". In fact there are a number of valid reasons to be interested in such 'low technology' :

- although advanced glazing technologies have shown considerable promise, technological

[1] IEA Task 18 finishes in 1997, promising further publication of spectral optical performance data.

problems and costs have limited their impacts thus far, and as noted by Littlefair [pp. 133, **21**] : '*Simulation of standard venetian blinds is important because they represent conventional window management practice, and are hence the benchmark against which innovative daylighting systems should be judged.*';

- radiation transport through these glazing systems is inherently complex, and is omitted or roughly approximated in many thermal, lighting and window design programs, e.g. [**22**];

- they can facilitate local user control and, hence, adaption, which is particularly important to user satisfaction in non-air conditioned environments e.g. [**3**,**23**]; while optimising their energy saving potential remains of interest [**24**, **25** , **26**, **27**, **28**].

- blinds continue to be the subject of new international research activity, e.g. [**29**, **30**, **31**].

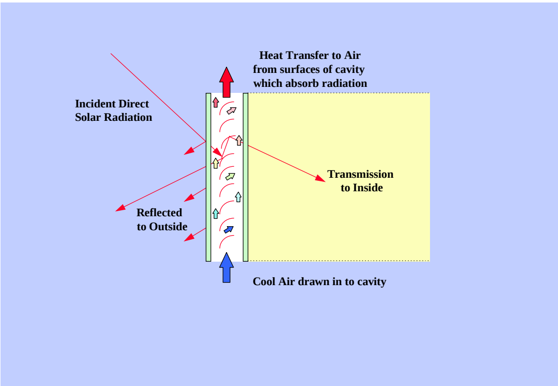

Figure 1 : Principles of Solar-induced Ventilation in a Facade containing Venetian Blinds

VENETIAN BLIND MODELLING

While the theory of radiation transport through blind systems has been outlined extensively in a number of papers published from the 1950's onwards, e.g. [**32**, **33**], and simplified parametric studies undertaken [**34**], only comparatively simple analytical models have been available until recently. Complex theoretical models were both impractical, given the comparative lack of computational power, and unnecessary given the ubiquity of blinds and the needs of HVAC design (e.g. Shading Coefficients [**35**,**36**].)

Even specialised programs such as WINDOW (then in Version 4.0) had yet to include blind models when the current research was initiated (early-1994), despite exploratory research [**37**], reiterating the difficulties alluded to above.

In 1987, Canadian Researchers developed a more comprehensive theoretical model for analysing interstitial blinds [**38**, **39**]. This radiation model is based on the (questionable) assumption of a single 'closed' cavity bounded by adjacent blind surfaces and inner and outer glass panes, diffuse inter-reflections within the cavity and employs the net-radiation (radiosity) method [**40**] for solution.

More recently a different (1-D) analytical blind 'cavity' model, suitable for incorporation into thermal simulation programs, has been proposed [**41**]. This splits the incident (solar) flux into (direct and diffuse) components, and then into directly transmitted and inter-reflected parts.

More complicated computational techniques, capable of 3-D treatments, are generally precluded from direct incorporation into thermal codes (much as for CFD models), but have found use in lighting design.

Several programs based on Monte Carlo Methods/Geometric Optics have been applied to problems such as the simulation of blinds, light-shelves and complex internal spaces. Apart from RADIANCE, results from at least two other programs which differ in respect of tracing forwards from light sources (and therefore not attempting to create a synthetic image) can be found in the literature. GÉNÉLUX is featured in [**4**], and has also recently been applied to the problem of inter-pane venetian blinds, again modelled as flat rectangular slats [**42**]. DAY3D [**43**], a model developed on the basis of an existing program for analysis of radiative heat transfer [**44**, **45**], has been used as part of a 'zero-energy' office design project.

OVERVIEW OF SIMULATION MODEL

Introduction to Monte Carlo Methods (MCM)

Radiation transport is a *natural stochastic* process, i.e. a sequence of random events, and therefore amenable to a Monte Carlo calculation, a *numerical* stochastic process. A *sophisticated* Monte Carlo approach is used [**46**], based on the simplifying macroscopic (non-quantum) concept of the *ray* from Geometric Optics (GO) [**47**].

Typically, a ray or *photon bundle* (as it is referred to in heat transfer texts, e.g.[**40**]) is traced from 'emission' at its parent surface (volume) through possible multiple scattering events until it is finally 'absorbed' . At each event, the direction of the bundle is determined by a *random number* (generated by a computational algorithm) scaled by the *probability distribution* that describes the physical process (i.e. scattering, reflection, refraction). After a sufficiently large number of rays have been traced, the outcome of the simulation should accurately represent the physical problem studied.

A good introduction to the use of MCM in lighting design can be found in [**48**], and their place in the context of alternative calculation techniques is assessed in [**49**]. The theoretical basis and broad implementation details for MCM are discussed in radiative heat transfer texts [**40**, **50**, **51**]. Detailed information on efficient practical implementation is sparse, necessitating a study of the advances in ray tracing for computer graphics/image synthesis [**14**, **52**, **53**, **54**, **55**] and in computational science/geometry [**56**, **57**, **58**].

This is particularly acute since in order to *halve* the *variance* (error) of a Monte Carlo estimate requires tracing *four* times as many rays [**46**].

Design of Simulation Model

A new (computer) simulation model is being developed according to the above principles (initially based on [**44**, **45**]), primarily as an academic research tool, with a view to wider usage. The design objectives include :

- view independence, i.e. tracing *forwards* from the radiation (light) source, rather than backwards from an 'eye-point' towards the light source as in ray tracing for image synthesis (e.g. RADIANCE);
- concentration on producing numerical data which can then be visualised, rather than on rendering a photo-realistic (synthetic) image;
- ability to generate data which can be exported to thermal simulation and CFD models;
- development of techniques to aid simulation, based on potential applications within the built environment, and reflecting limited computer resources likely to be available in many design offices;
- modular format for re-use and extension of code.

The model is being developed on UNIX and PC platforms using Fortran 90 (despite compiler reliability problems). Input and output is currently from/to ASCII text files. More details can be found via the Internet at the URL given above.

The simulation model itself, and the results presented below, are being validated against analytical solutions, empirical data and existing models/calculation techniques wherever possible, in accordance with the conceptual framework proposed by Bloomfield et al [**59**]. Due to the stochastic nature of MCM, error analysis can be quite involved, but can be conceived in a conventional way by considering each simulation as an experiment, e.g. [**60**]. 'True' error analysis is more complex still, requiring empirical validation.

Simulation of Solar Radiation/Daylighting

The simulation model adapts traditional approaches to the problem :

1. Calculate the irradiance (illuminance) incident on a ***tilted (inclined) surface*** using existing numerical models or empirical data, and make additional assumptions about its angular distribution.

2. Create an ***artificial 'sky'*** and an ***artificial 'sun'*** within the computational model, to simulate the radiance (luminance) distributions 'seen' under a range of skies.

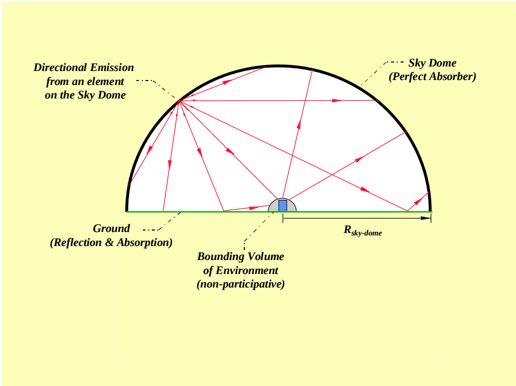

Figure 2 : Concept of Artificial Sky for simulating Diffuse Solar Radiation via 'Brute-Force' Sampling

These approaches (and their limitations) are discussed in more detail in [**61**].

Simple Window Simulator

This 'tilted surface' approach can be of practical use in simulating the performance of a window or glazing unit, providing its boundaries are essentially planar (2-D). An example 'experimental rig' is shown in *Figure 3*.

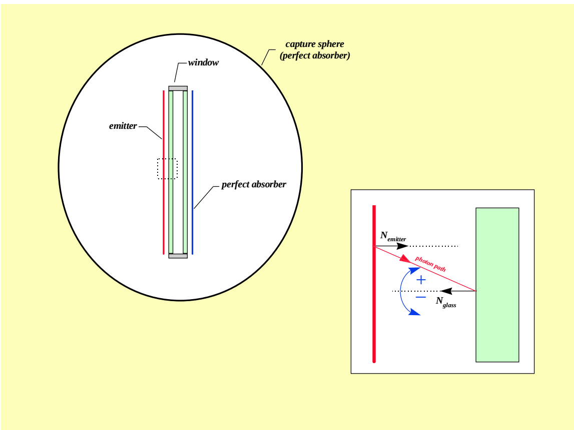

Figure 3 : Simulation of (Direct) Solar Radiation for a standard Glazing Unit

Direct solar radiation is modelled as (specular) emission in a single direction (infinitessimal solid angle) at points uniformly distributed on the surface of the emitter. (It should also be possible to simulate spectral dependence for standardised reference sources [**62**] and various glasses [**63**]).

The *emitter* and *absorber* absorb all incident radiation[2], so that a simulation will give statistical estimates of the overall performance of the glazing unit as a 'single' component (e.g. transmission; reflection; absorption of solar radiation).

The *capture sphere* prevents rays (and hence energy) escaping or 'leaking' from the system, due to numerical precision problems (inherent with floating point arithmetic on digital computers), so that the Monte Carlo estimates remain unbiased.

However, as soon as the bounding surfaces of the glazing system become non-planar (i.e. truly 3-D), e.g. by the introduction of a light shelf, then this approach will fail. This is also the case where the radiation distribution within a room or building is of interest. Hence the need for an 'artificial sky' approach.

EXPERIMENTS

The main point is to show the 3-D treatment of fenestration systems via use of the *Simple Window Simulator*, and the correspondence of the results to both intuitive and observed phenomena.

In each case, the following assumptions apply :

- a sealed glazing unit of dimensions 3m high x 1m width x variable depth is modelled;
- simulations were carried out at 5º intervals for the solar angle of incidence (altitude), and the solar azimuth remained unaltered (normal to the outer pane);
- convergence was determined using the criteria proposed in [**45**], which gives most weight to those surfaces/bodies absorbing the largest fraction of the incident radiation (i.e. "one is 95% confident that the true mean lies within +/- 1% of the estimated values").

- the incident (solar) radiation is unpolarised;
- a single quasi-monochromatic case has been considered, so that the optical properties of the glass and frame represent mean values valid within the visible spectrum (i.e. appropriate for light / solar radiation). The index of refraction is denoted **n**, and the absorption coefficient, **a**, (**a** is related to the coefficient of extinction, **k**) [**40**].

- Thermal radiation, conduction and convection are not considered;

- for double-glazing, the internal cavity is assumed to be filled with air (a non-participating medium);
- clear float glass is modelled as a homogeneous di-electric medium, with absorption (but no scattering) allowed along the path length within the panes. The internal and external boundaries are assumed to be optically smooth (polished);
- the window frame is assumed to be aluminium, i.e. an absorbing medium, and also optically smooth;
- the corresponding probability density distributions for (idealised specular or mirror) reflection and refraction at the various air/glass/frame interfaces (boundaries between materials) have been predicted from Fresnel's and Snell's Laws [**40**].

Performance of Clear Single and Double Glazing

Initial simulations were carried out on basic single and double-glazed units to test the validity of the simulation model.

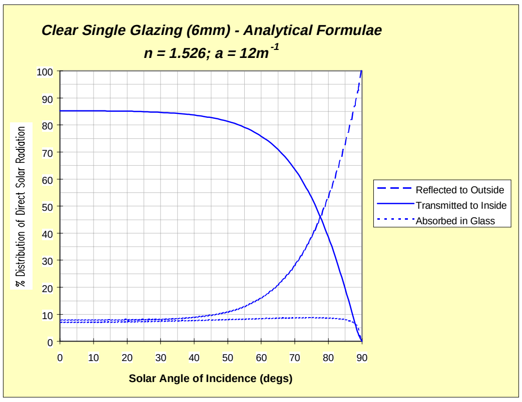

Figure 4 : Single-Glazing : Analytical Performance Curves

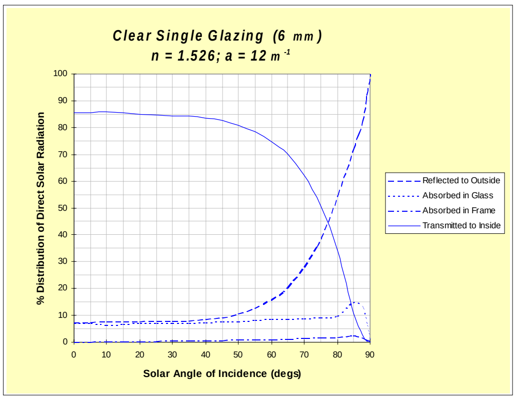

Figure 5 : Simulated Performance of Single-Glazed Window

Figure 4 is based on standard analytical formulae [**40**] - where the glass is assumed to be a 1-D semi-

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2 note that the properties of the emitter are <u>not</u> physically valid, i.e. it does not obey Kirchoff's Law.

infinite medium - and provides a reference against which to compare the simulation results for a 3-D single-glazed window (incorporating a frame) shown in *Figure 5*.

As can be seen from the above graphs, the predicted performance obtained by the Monte Carlo Simulation is as would be expected (also indicating the validity of the theory and assumptions implicit in the analytical formulae).

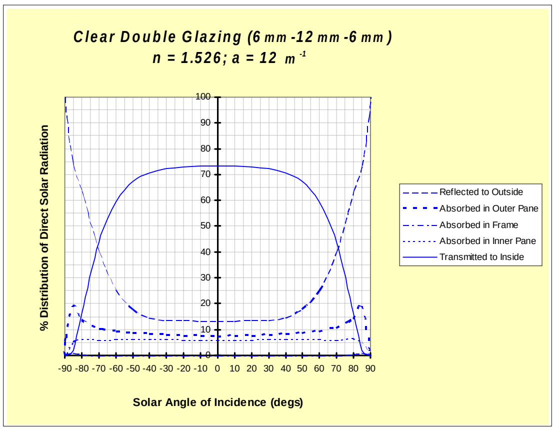


Figure 6 : Simulated Performance of Double-Glazed Window

The symmetry observed in the case of double-glazing, shown in *Figure 6*, also serves to inspire some confidence in the model.

Note the presence of a peak in the absorption of the panes in *Figure 5 & 6*, as the incident solar radiation approaches the grazing angle, due to the phenomenon of *total internal reflection* (this is accentuated in these graphs because all internal reflections, including those at the glass/frame interface, are modelled as specular).

Performance of Double Glazing containing Interstitial Blinds

The next modelling task was to incorporate interstitial venetian blinds within a double glazing unit. For the purposes of this simulation the internal cavity was widened and 40 blind slats inserted[3]. The geometry is illustrated in *Figure 7*.

In general, individual blind slats will have a non-negligible thickness, and have complex spectral optical properties corresponding to a layered material, i.e. typically a paint or plastic coating on top of a plastic or metallic substrate.

[3] these dimensions were chosen due to an interest in subsequently modelling solar-induced ventilation within the cavity via a CFD model.

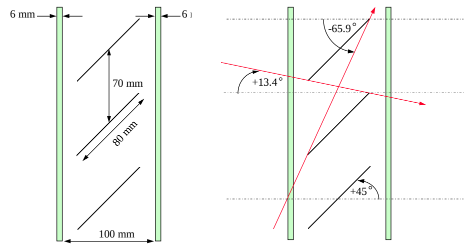


Figure 7 : Cross-Sectional Geometry for Interstitial Blinds

For simplicity, idealised radiative properties have been assumed for opaque blinds, representing limiting cases :

'Material' Descriptor	Reflective Behaviour	Reflectivity, ρ	Absorptivity α	Transmissivity τ
White Specular	Specular	0.9	0.1	0.0
White Diffuse	Lambertian	0.9	0.1	0.0
Black Diffuse	Lambertian	0.1	0.9	0.0

(note that allowing transmission, e.g. to simulate perforated blinds, or even glass blinds is readily possible).

Figure 8 and 9 give an indication of the impact of the choice of blind material for two representative slat angles.

Note the slight unexpected asymmetry in the curves when the slats are horizontal (at 0°), which is not present for the double glazing unit on its own. This is used to illustrate possible sources of error [**60**], e.g. :

- *stochastic* errors : each data point represents only the mean of two simulations, whereas ideally perhaps 20-30 are required;
- *systematic* errors : if after completing these further simulations the bias is still present, then there must be an error in the input and/or simulation model.

- in this case it proved to be a slight (but hard to detect) error in the model itself.

- Since this paper only considers a few example studies for 'idealised' blind materials, a qualitative interpretation of the results will be adopted. This will be necessarily subjective, since the 'optimal' choice of blind will depend on many diverse factors such as the design strategy for the building, the climate, the orientation of the particular window/facade, whether the blind positions are automatically controlled and so on.

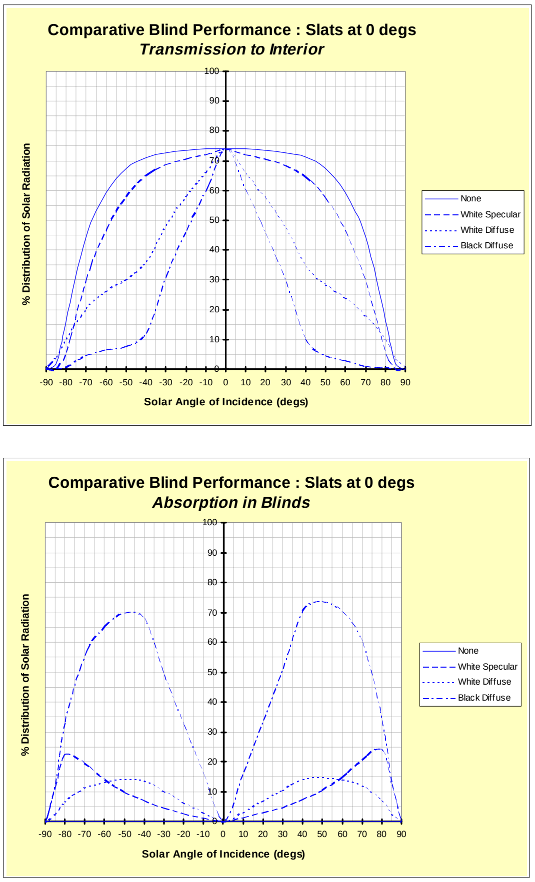


Figure 8 : Comparative Blind Performances at 0° tilt

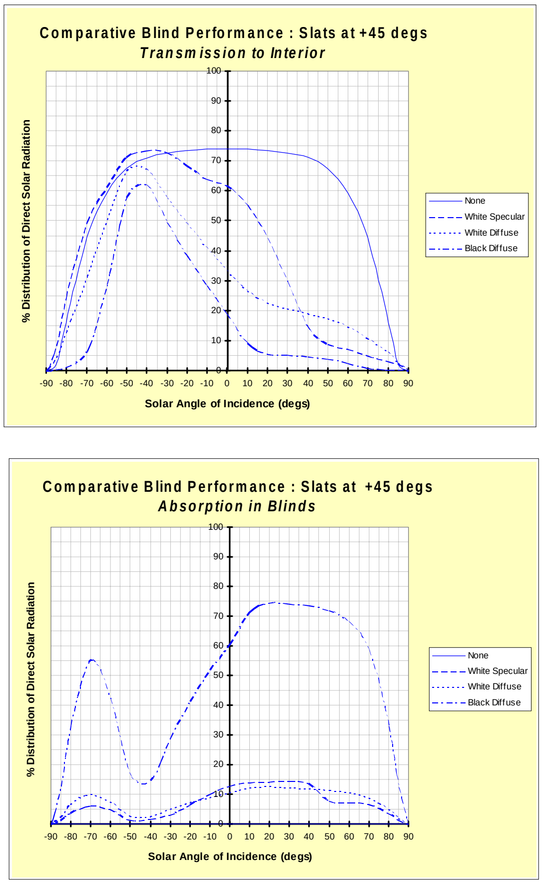


Figure 9 : Comparative Blind Performances at +45° tilt

Black diffuse blinds would provide a high level of solar protection, however, the radiant energy removed would remain within the glazing system and reach the inside via thermal radiation, conduction and convection.

Despite the asymmetry in *Figure 8*, it is clear that in a horizontal position, very highly reflective blinds (e.g. with a glossy finish) provide little protection from the ingress of direct solar radiation.
An alternative interpretation would be that they would enhance light transmission on overcast days where the blinds have been left down (This latter conclusion is suggested by considering the area under each transmission curve, and assuming that diffuse radiation will be approximately isotropically diffuse).

At a slat angle of 45°, it can broadly be inferred (not unexpectedly), that highly reflective specular blinds :

- reduce transmission of direct solar radiation at high sun angles (> slat angle), since due to the geometry, incident radiation will be reflected from the blind slats back out towards the outside;

- enhance transmission of direct solar radiation at low sun angles (< slat angle), suitable for passive solar heating approaches, whilst preventing glare;

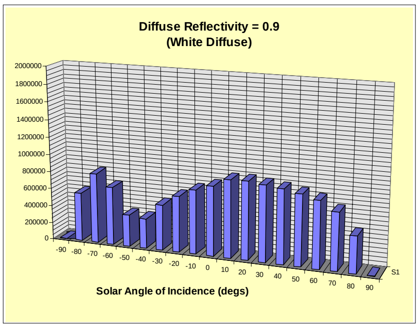
- enhance transmission of diffuse radiation, so that they will tend to transmit more light, and any increase in the diffuse solar load during summer should be more than compensated for by the reduced transmission at high solar altitudes.

- alternatively, it could be said that highly reflective diffuse blinds would give better solar protection at lower solar altitudes.

It is important to emphasise that the blind material properties used are idealised, and that the actual properties will lie somewhere between the limiting cases shown. There will also be further complicating factors such as the build up of dust on the slat surfaces and so on.

The graphs in *Figure 10* give some idea of the number of rays that were traced with the slats at 45° before convergence was achieved (the *white specular* and *white diffuse* runs were essentially similar.). Somewhat surprisingly, the slowest simulation was for the black diffuse case, since although one would expect there to be fewer inter-reflections, there are a large number of slats all absorbing significant amounts of radiation, which becomes the dominant factor in the convergence criterion. For highly reflective blinds, the dominant influences are the panes and the absorber and emitter.

The large number of rays which must be traced and the large number of surfaces with which they can intersect illustrate the need for ray acceleration techniques. These are currently being developed and will give a better indication of run-times on various platforms.



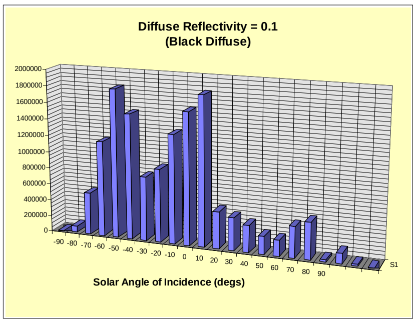


Figure 10 : The Number of Rays emitted in order to achieve Convergence for Slats tilted at +45°

CONCLUSIONS

This paper illustrates the potential power in using a combination of Monte Carlo Methods and ray-tracing techniques to explore the behaviour of complex fenestration systems. This flexibility does, however, come at a price in terms of programming complexity, computational time and interpretation of error.
Future work will concentrate on different glazing-blind combinations, the modelling of spectral (wavelength) dependence (both of sources and materials) and allowing the curvature of individual blind slats to be properly considered (i.e. by modelling them as 'partial' cylinders of large radius).

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