The Appropriateness of Simplified Solar Algorithms

Dr. J.P. Allen and Dr. J.K. Whittle

Department of Architecture
University of Nottingham
University Park
Nottingham, NG7 2RD UK

KEYWORDS

Dynamic Thermal Models, Review of Algorithms, Sensitivity studies, Solar Distribution, Solar Transmission, Validation.

Solar processes are the dominant driving forces of this planet's climate. It is therefore not surprising that much research has been directed at harnessing the available solar energy. Much of this research has been on active solar collectors and passive solar design features in building design. This has been reflected in the production of several algorithms describing particular solar features. These algorithms have been incorporated into already existing or developing dynamic thermal computer models for the simulation of the energy flows within the building envelope. Relatively little work has been performed to assess whether these algorithms are adequate or indeed appropriate. Part of the thermal model validation exercise has been to look in detail at various sub-processes and algorithms, including the treatment of glazing and the distribution of solar radiation within the building envelope. An extensive review of such algorithms has been performed. Sensitivity studies have enabled the relative merits of the various algorithms to be assesed. The results of the studies have allowed the appropriateness of the currently used solar algorithms to be established.

La Justesse des Algorithmes Solaires Simplifies.

Dr. J.P. Allen and Dr. J.K. Whittle

Department of Architecture
University of Nottingham
University Park
Nottingham, NG7 2RD UK

KEYWORDS

La Distribution Solaire, les Etudes de Sensibilite, les Modeles Thermiques Dynamiques, la Revue des Algorithmes, la Transmission Solaire, Validation.

Les processus solaires sont les forces agissantes et dominants du climat de ce planete. Il n'est donc pas etonnant que la recherche ait ete dirigee vers l'harnachement de l'energie solaire disponible. La plupart de ce travail a ete faite sur les receveurs solaires actives et les caracteristiques solaires, passives du dessein dans la conception du batiment. Ceci a ete reflete dans la production de plusieurs algorithmes qui decrivent des carateristiques solaires particulieres. Ces algorithmes ont ete incorporees dans des modeles d'ordinateur thermiques et dynamiques qui existent deja on qui sont en train de developpement pour la simulation du flux energique dans le cadre du batiment. Relativement peu de travail a ete execute pour evaluer si ces algorithmes sont suffisants on meme justes. Une partie de l'exercise de la validation du modele thermique a ete de regarder en detail les sous-processus et les algorithmes, y compris le traitement de vitrage et la distribution du rayonnement solaire a l'interieur du cadre du batiment. Une revue approfondie de tels algorithmes a ete executee. On a pu constater les valeurs relatives des divers algorithmes par des etudes de sensibilite. Les resultats de ces etudes ont laisse etablir la justesse des algorithmes solaires en usage courant.

Introduction

Solar radiation is recognised as being a valuable source of free energy. If the designer is to use this energy source to his best advantage he requires a detailed understanding of the thermal processes and interactions which take place within a building. Perhaps the most effective tool with which this understanding can be achieved is the dynamic thermal model. To date a large part of the thermal modelling research effort has been devoted to developing and extending these simulation models, very little has gone into developing techniques for checking the models or into assessing the individual algorithms which make up the models. The work described here forms part of the UK Thermal Model Validation Exercise, funded by SERC (UK Science and Engineering Research Council), which was initiated in an attempt to partly redress this imbalance.

The overall methodology adopted by the research team is a development of previous efforts at validation, notably that of SERI [1] (Solar Energy Research Institute, USA), and has been outlined elsewhere [2]. Part of this methodology is a study of individual model algorithms, the steps followed in performing this algorithm study are outlined in the accompanying paper [3], which also details how the significances of the errors found in the study are determined. In this paper the scope of the solar radiation work will be outlined and some examples of the modelling problems studied will be given.

The task of assessing the approaches adopted by various authors to modelling the interactions between short-wave radiation and a building is best handled by sub-dividing the process into four parts:

1) Calculation of solar radiation into a zone,
2) Determining the distribution of the radiation around the zone,
3) Evaluating the amount of radiation escaping from the zone,
4) Basic solar geometry.

For each (except 4 which formed part of a separate study) current modelling practice was compared against the precise solution and the implications of the various simplifications and assumptions were investigated. The results of these studies are necessarily voluminous, therefore at this interim stage of the work only general conclusions can be given.

1) Solar radiation entering a zone.

The calculations which determine the amount of solar radiation entering a zone reveal to the designer the amount of free energy available for space

heating and the amount of excess energy present which may cause overheating. Thus they form a fundamental part of the simulation process. Two of the algorithms studied in this part were; shading by the building facade and determining the glazing optical properties.

Self-shading by fins, overhangs or simply the wall thickness in the case of windows which are set-back, will reduce or even prevent completely the direct beam solar radiation from reaching the glazing and entering a zone. Despite their importance these shading calculations are often omitted as they increase the computation time and the amount of building geometry information required, information which the designer may not have or not wish to consider at an early stage in the design. The magnitudes of the errors associated with such omissions were determined using a clear sky solar radiation model, the magnitudes predicted would thus be worst case values and would not be site specific (as would have been the case had data from standard meteorological tapes been used instead).

An example of a typical simplification is for shading elements on a building facade to be treated as being infinite rather than finite in length (for eg. SERIRES). This simplification produces an underestimate of the total transmitted radiation over a year of typically less than 1% . In this example the horizontal shading element modelled was 1m wide and 0.1m deep and was situated directly above a window 1m square. If, instead, the projection is neglected completely then this results in the total annual transmitted radiation being overestimated by between 5% and 10%, depending on whether the site is on the arctic circle or equator respectively. In the absence of shading, neglecting window set-back leads to an overestimate of the total annual transmitted direct beam radiation of greater than 30% for the equator, to around 15% at the arctic circle (window 1.0m square, 100mm set-back). From the figures it is clear that what at first appears to be a minor omission in the simulation of a building can lead to significant differences in the energy balance of that building.

The calculations presented so far have assumed that the external shading elements cause pure shading only. Where such external elements are situated on both sides of the glazing (left & right or above & below), those elements on the non-shading side will be acting as diffuse reflectors, adding to the radiation transmitted into the zone. Continuing with the set-back example, if the albedo of the surface surrounding the window is assumed to be 0.4 (i.e. only 40% of the radiation incident on the surround is reflected) then it can be shown that of the reflected portion only 30% will pass through the glazing. The intensity of the reflected radiation passing into a room is thus about 10 times smaller than the intensity of the radiation prevented from reaching the window by the shading, and is just 1% of the total transmitted direct beam radiation. In a small room (3mx3mx2.1m, average wall U-value 1.0 $W/m^2/K$)

this represents a rise in the air temperature of about 0.2K over one hour, so could be ignored in many cases.

Of similar computational length are the expressions required to determine the optical properties of the glazing. Again simplifications are common; calculations performed only on selected days, polynomial fits to the transmissivity curves, evaluation of the values for selected incidence angles with linear interpolation to determine the required values during the simulation, etc. As was also found in the case of shading, reducing the computational overheads by evaluating the required values only on selected days proved adequate for simulations over an annual period but became increasingly unsatisfactory as the period of the simulation approached a few days. In contrast a linear interpolation approach for determining the transmissivity values was shown to be particularly effective. For example, if the transmissivity curve was divided into 9 equal length segments (as in the model HTB2) the maximum evaluation error was in all cases less than 1%. Linear interpolation also has the advantage of offering a substantial saving in computation at run time over the traditional repeated evaluation of optical properties using standard Fresnel equations.

The examples above were all evaluated for direct beam radiation, for which it is straightforward to determine the angle of incidence on the glazing. In the case of the diffuse radiation component the angle of incidence depends on the sky radiation model. If an isotropic sky is assumed (uniform intensity over the whole sky vault) a constant incidence angle independent of the solar position can be used, the angle used giving a transmissivity value equivalent to the average transmissivity over all incidence angles (such an approach is used in SERIRES and ESP). It should be noted that a different angle of incidence applies for calculating the absorption of diffuse radiation by the glazing. If the sky diffuse component is assumed to be anisotropically distributed then the diffuse incidence angle must be related to the solar position. An example of this is DEROB-IUA, in which the diffuse is concentrated around the solar disc and in the region between the solar disc and the zenith. This generates a possibly more realistic distribution of the diffuse about the sky, particularly where glazed surfaces facing away from the sun are involved.

2) Solar distribution within a room.

In contrast to the calculations for the solar radiation transmitted into a zone, the precise calculation of solar distribution within a zone is usually considered secondary. Several arguments in support of this are often given; the constructions of most walls in a building are sufficiently uniform for it not to matter on which wall the radiation falls, that the bulk of incoming radiation falls on the floor and that a

precise treatment is unnecessary because real rooms will have furniture and fittings. As a consequence models such as SERIRES and HTB2 do not model the spatial geometry of the zone, leaving the decision of where to put the radiation to the user.

The form of the calculations differ depending on whether the radiation is diffuse or direct. The direct component calculations are the most complex, as they include calculation of sun-patch positions. This involves the solution of three-dimensional optical geometry - a task to which digital computers are well suited. However, a consequence of the high computational burden involved with these calculations is that they are often simplified, for example by specifying that all of the incoming radiation is to fall on the floor of the zone. After the initial distribution, part of the direct component is absorbed and part reflected, the reflected component is always assumed to be diffusely reflected (anyone observing a polished floor will know that this is not the case). Diffuse transmitted and diffuse reflected can then be combined and distributed in a similar manner. The radiation then undergoes a number of reflections until eventually the continuing radiation reaches an intensity sufficiently small for further reflections to be ignored, common modelling practice is to truncate this series of decays.

A topic investigated in this section was the effect on the convective transfer from partially irradiated walls of the 1-D heat flow assumption (implemented in all the models studied). It was reported in the accompanying paper [3] that the magnitude of the convection coefficient depends on the length of the heated surface and temperature of the surface, thus a discrepancy will arise if one adheres to this 1-D assumption, see for example [4]. The errors in surface temperature and flux due to this assumption can be shown to increase as the size of the insolated area decreases. An initial assessment of the magnitude of this error was performed by evaluating the heat flux balance for the surface when under steady-state conditions. If, say, the intensity of the radiation is 500 W/m^2 and the patch covers the lower fifth of the wall surface, then the 1-D assumption distributes this radiation over the whole wall as a flux of 100 W/m^2. Our studies show that this leads to an underestimate of the convective flux from the wall surface to the zone air of between 10% and 20%, depending on wall resistance. However, the flux forms only about 15% of the total heat transfer away from the wall surface. In the small room (3mx3mx2.1m) used above this assumption would, over an hour, produce a temperature rise error of less than 0.4K, which could justifiably be ignored when one considers the magnitudes of other errors present. To improve on the 1-D assumption would require a fundamental re-write of all the models considered.

Another topic considered has been the use of an area-weighted distribution for the diffusely reflected radiation as opposed to the more exact view-factor based distribution. Under the area-weighted scheme the reflected radiation is apportioned around a room according to the areas of the receiving surfaces, whereas the view-factor approach evaluates the areas of the receiving surfaces as 'seen' from the reflecting surface and then distributes the radiation. The latter approach again is computationally complex and in the case of re-entrant geometries (eg. L-shaped room) even more so.

Several geometries were studied, with several combinations of surface albedos. As is found in work on long-wave radiation transfer [5], the further the zone geometry deviates from a cube the greater the errors. Consider for example a rectangular zone, formed by joining two cubic zones, with all surfaces having an identical albedo of 0.5. If the radiation starts from one of the smaller end surfaces then using an area-weighted distribution will lead to an underestimate of the radiation received by the larger surfaces of around 3%, however the radiation received by the other end surface will be overestimated to the extent of 30%. Expressing the errors in terms of the total radiation present they become 0.8% and 2.5% respectively. Thus if the two end surfaces were glazed (assuming glazing with an effective diffuse reflectivity of 0.5) the area-weighted distribution would in this case overestimate the diffuse radiation lost from the room by around 2.5%.

3) Radiation passing out of a zone

The calculations for radiation leaving a zone are essentially just an extension of the distribution calculations. Like those used to determine the radiation initially entering the zone, they form an important part in the overall zone energy balance computations. Gross simplifications are common, for reasons given in section 2. An example of this is to be found in SERIRES, the fraction of the incoming solar radiation lost from a room is specified simply by a user defined constant.

The final example considered here, is that of calculating the passage of direct beam radiation through a zone and across internal windows. To evaluate the radiation passing directly through a zone one must perform geometrical calculations involving the determination of the intersection of three-dimensional planes. As mentioned earlier, this task is computationally expensive. The approach adopted in those programs studied which included spatial geometry was therefore to subdivide the receiving surface into a grid-mesh of points and then to project these points parallel with the rays of the sun onto the glazing, testing each for containment. For example the implementation used in DEROB-IUA subdivided each receiving surface into a rectangular mesh of 3x3 grid points. The number of mesh points is fixed in this case, thus no consideration is given to establishing an appropriate mesh size based on the rate at which the sunpatch will move across the surface. Again errors of the order +/- 0.5K can arise in the zone temperature.

Conclusions

In simulating the interaction between short-wave solar radiation and building fabric, simulation models have to incorporate by necessity many simplifications and assumptions. The user, however, is rarely given guidance on how these approximations will affect simulation accuracy. This is unsatisfactory.

The precise influence of errors is site and geometry specific, thus any conclusions from a study such as this can only be general. If users are to have confidence in the simulation results, the model must therefore allow both the full calculations required for error estimates and simplified calculations for rapid solution once the validity of such simplifications has been shown.

Versions/listing date of models cited and acknowledgement

DEROB-IUA 1.0, Jan.1985; ESP (ABACUS,UK), Jan.1985; HTB2 1.0 (UWIST,UK), Nov.1984; SERIRES Jun.1984

This work was funded by the Science and Engineering Research Council under contract no. GR/C/62864.

References

1) D.Wortman,B.O'Doherty,R.Judkoff, The implementation of an Analytical Verification Technique on three building energy analysis codes, Proc ASME Solar Energy Division, 3rd Ann. Conf. on Systems Simulation and Economic Analysis, pp.268-276, May (1981).

2)D.Bloomfield, Appraisal techniques for methods of calculating the thermal performance of buildings, BSER&T,6,(1),pp.13-20,(1985).

3)J.P.Allen,J.K.Whittle, An appraisal of heat transfer coefficient algorithms in dynamic thermal models, presented at CIB.86, Washington, (Sept.,1986).

4)J.M.Connolly,C.E.Bingham,J.K.E.Ortega, Computer modelling of thermal storage walls,Proc.Ann.Meet.Am.Sect.Int.Sol.Energy Soc., pp.918-922, (1980).

5)P.Stefanizzi, The internal longwave radiation exchange in thermal models, SERC Validation project Working group internal report,(June 1985).