The Development of an Hourly Thermal Simulation Program for Use in the Australian Nationwide House Energy Rating Scheme

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ABSTRACT

The Australian Nationwide House Energy Rating Scheme is aimed at improving the energy efficiency of residential building envelopes. The technical basis of the scheme is a multi-zone hourly thermal simulation program, which will be used to calculate annual heating and cooling energy requirements and temperatures in the building to be rated, from which a star rating is derived. This paper gives an overview of the software, and describes the improvements to the glazing model and the model for slab-on-ground construction that were undertaken as part of its development.

INTRODUCTION

Australia's large area encompasses a wide range of climates. At its northern end, Darwin (latitude 12 degrees south) has a hot-humid climate, while at its southern end, Hobart (latitude 43 degrees south) has a cool-temperate climate. Most of the population lives in the very moderate climates of the east coast. This, coupled with the relatively low cost of energy, has meant that until recently little has been done to significantly improve the energy efficiency of residential building envelopes, with the exception that ceiling, and to a lesser extent wall, insulation has become common in some states.

In Australia residences consume about 12% of total end-use energy. Thirty-five percent of this is used for space heating and cooling, the vast majority being for heating. There is thus considerable potential for reducing the residential energy consumption attributable to the building envelope. Furthermore, there is a trend for building designs that are suitable for temperate southern climates to be built in the hot-humid northern climates, for which they are much less appropriate than the traditional local designs. This, coupled with rising expectations for indoor comfort, will lead to a greater demand for air conditioning. This is a situation to be avoided, since it leads to greater greenhouse gas emissions, and imposes additional costs and inefficiencies on electricity utilities, which must satisfy an increased peak demand which only occurs over a very small part of the year.

The Nationwide House Energy Rating Scheme (NatHERS) arose as a result of a commitment by Australia's Commonwealth, State and Territory governments to improve the energy efficiency of buildings, as part of their Greenhouse Response Strategy. The objectives of the scheme are:

- to assist the public and the building industry to identify the extent to which a new or existing house has the potential, through its design and construction, to be of high efficiency in its use of space heating and cooling energy;
- to facilitate rating of the thermal efficiency of dwelling design and construction, in a manner that is nationally coordinated and consistent, and is regionally sensitive to variations in climate, housing design and other factors.

Although there have been previous attempts to develop such schemes in Australia, this is the first adequately-funded nationwide initiative of this type. As well as the very common detached single-family houses, the scheme will also encompass medium-density housing developments as well as low-rise apartment buildings. Buildings will be rated on a scale of 0 to 5 stars. In the scheme's initial implementation, the star rating will be calculated from the heating and cooling energy requirements; in the future indoor comfort conditions in the absence of heating or cooling may be used as the basis of a rating for some locations.

It was decided quite early in the development process that the rating would be based on computer simulation of the building, using hourly calculations over a full year. This will enable the wide range of climates to be better taken into account, and also has the advantage that each rating is done for the individual building, rather than having to be related to a “standard” building on which a simpler system might be based. The CHEETAH package, developed by the CSIRO Division of Building, Construction and Engineering (Delsante, 1987), was chosen as the basis of the simulation tool. This paper gives an overview of the rating scheme software, and describes some of the improvements in the thermal model that were undertaken as part of the software’s development.

AN OVERVIEW OF THE NATHERS SOFTWARE

The software consists of a Windows-based data entry front-end, communicating via a transfer text file with the simulation engine, and a Windows-based reporting package.

Data entry

Data entry is via four main screens or forms: a Main Form, which contains the basic job details and gives access to the other forms; a Construction Form, which allows the user to select a main and two alternative constructions for the windows, walls, floors, etc from drop-down lists; the Dimensions Form, in which lengths and/or areas are entered for the various elements on subsidiary zone forms; and a General Form, in which information about infiltration and the potential for cross-ventilation is entered via simple Yes/No responses. Information about indoor and outdoor user-operable shading devices, and fixed shading from overhangs, pergolas and other buildings, is also entered in these forms.

The current front-end deliberately restricts the full flexibility of the simulation engine in the interests of keeping the data input requirements to a minimum. For example, only four habitable zones are allowed: Living, Bedroom, Other Conditioned, and Unconditioned (e.g. laundries, and other service areas). Roofspace and sub-floor zones are formed automatically (if necessary). Similarly, because its primary purpose is as a rating tool, there is no provision for the user to change the data for occupant behaviour, e.g. times of heating and cooling, and operation of curtains, external blinds, and windows.

The simulation engine

The simulation engine calculates hourly temperatures, and if required heating and cooling energy requirements, in each of several zones. The calculation is based on the zone response factor method. Each building element is treated as a multi-layer slab, the frequency response of which is calculated via matrix multiplication over the range of frequencies for which the response is non-zero (e.g. Carlsaw and Jaeger, 1959). In the frequency domain, a heat balance for each zone is struck, giving the zone frequency response to sinusoidal external drivers (e.g. outdoor temperature). The frequency response is converted to a zone transient response via linear system theory (e.g. Papoulis, 1962). The transient response to a unit step or triangular pulse is easily derived, and the outdoor temperature, solar radiation, and other heat flow drivers are approximated as series of step or triangular pulses. A time step of one hour is used. Details can be found in Walsh and Delsante (1983).

This main advantages of this method are:

- there are no lumping errors introduced, as would occur with numerical solutions of heat flow through multi-layer slabs;
- execution times are small (e.g. 60 seconds for a full year of hourly calculations on a typical personal computer). This feature is essential if the software is to be used for rating purposes.

The main disadvantage is that the properties of the thermal network representing the building must be constant in time. This presents difficulties when modelling wind-speed-dependent infiltration and ventilation, or time-varying surface heat transfer coefficients. The treatment of time-dependent properties will be discussed below in the context of the glazing model.

Output reporting

The reporting facility produces several simple output screens. The main screen gives a brief building description, and the annual total heating, sensible cooling and latent cooling energy requirements for the conditioned zones (in MJ/m^2 of conditioned floor area). If the run was done in rating mode it also shows the star rating for the building, which is calculated from the energy total.

Two other output screens are available, which give information about the temperatures in up to three zones. The user can configure the temperature reports by choosing the months or seasons of interest, the times of interest, and the upper and lower limits of the comfortable temperature range. The degree hours screen gives the number of underheating and overheating degree hours for each selected zone. Overheating degree hours are simply the cumulative difference between the zone temperature at each hour and the specified upper limit of the comfort range (whenever this is positive) for the chosen times and period; underheating degree hours are defined similarly. Finally, the temperature information can be displayed as histograms of occurrences of temperatures in 1-degree bins, for the selected zones, hours and period.

Occupant behaviour

One of the problems in modelling residences in temperate climates, especially the single-family detached houses common in Australia, is that occupant behaviour has a great influence on the building performance. The simulation engine can model several aspects of occupant behaviour, namely the operation of indoor and/or outdoor curtains and blinds, opening of windows to increase ventilation, and hourly schedules for indoor heat gains and heating and cooling. However for rating purposes such behaviour must fixed to allow different building envelopes to be fairly compared. The key element is thermostat settings for heating and cooling (and of course the times for which heating and cooling is available). The rating is based on the sum of heating and cooling energy requirements. In a moderate climate such as that of Sydney, a one degree increase in the heating and cooling thermostat settings can change the total energy from being cooling-dominated to heating-dominated. Thus the thermostat settings must be chosen with care, and the final values are still under consideration.

Weather data

Hourly weather data (dry and wet-bulb temperature, wind speed, cloud cover and direct and diffuse solar radiation) for one year is required for the NatHERS software. Solar radiation measuring stations are very sparse in Australia: of the 59 available sites with adequate data, 28 were selected to cover the country. Each postcode is associated with one of the 28 data sets. Long-term average data, simulation of building performance, and any other relevant information was used to determine the association where hourly data were not available. The relevant weather data file is automatically called up when the user enters the building’s postcode on the main input data form.

AN IMPROVED GLAZING MODEL

The original glazing model in CHEETAH is quite simple. The angular dependence of solar transmittance and absorptance is calculated correctly only for 3 mm clear glass. For all other glazing, the solar heat gain is obtained by multiplying the solar heat gain for clear single glazing by a fixed shading coefficient. This in effect assumes that the functional dependence of transmittance and absorptance on angle of incidence was the same for all glazing, which is not the case. The convective and radiative heat transfer coefficients on the outdoor and indoor side of the glazing are assumed to be constant. Finally, window frames are not included.

As buildings become better insulated, heat flow through windows becomes relatively more important. There is also growing interest in glazings with better performance than the standard single clear glazing with an unbroken aluminium frame common in Australian domestic construction. For these reasons, a new glazing model, which addressed the deficiencies noted above, was developed and implemented in the NatHERS software, and is described below.

Treatment of solar absorptance and transmittance

The overall solar transmittance, *T*, of the glazing is calculated hourly as a function of the angle of incidence, *i*. This is done via the following equation:

$$T = \frac{a + cx + ex^2}{1 + bx + dx^2 + fx^3}, \qquad (1)$$

where $x = \cos(i)$, and *a*, *b*, *c*, *d*, *e*, and *f* are constants obtained by curve-fitting (1) to suitable data. The same type of equation is used for the absorptance of each pane. The transmittance and absorptance as a function of angle of incidence can be obtained from a variety of sources, for example by using the Window 4.1 program

(Lawrence Berkeley Laboratory, 1993). Figure 1 compares the transmittance data for a low-emissivity high-transmittance double-glazing unit with the curve-fit. To illustrate the difference between the shape of the actual transmittance curve and that derived from single glazing via a shading coefficient, Fig. 1 also shows the transmittance for single glazing, scaled so that it agrees with the exact value at zero angle of incidence. Clearly the new method produces much more accurate results.

Calculation of outdoor convective heat transfer coefficients

In a recent study, Yazdanian and Klems (1994) measured convective heat transfer coefficients at the outdoor surface of a window in their MoWitt (Mobile Window Thermal Test) facility, a free-standing house-sized structure. In comparison with some commonly-used correlations, their results gave consistently lower values, and in some cases the differences were extremely large. From curve-fits to their data they developed the following equations:

Windward side:

$$h_c = \sqrt{\left(0.84(\Delta T)^{1/3}\right)^2 + \left(2.38v^{0.89}\right)^2}\ , \qquad (2)$$

where h_c is the convective heat transfer coefficient, ΔT is the temperature difference between the surface and the air, and v is the local wind speed at 10 m height.

Leeward side:

$$h_c = \sqrt{\left(0.84(\Delta T)^{1/3}\right)^2 + \left(2.86v^{0.617}\right)^2}\ . \qquad (3)$$

The MoWitt results were adopted for the NatHERS software, with some modifications. First, only the windward equation, (2), was used. This is because the current weather data set used with NatHERS does not contain wind direction, and because much more data were collected on the windward side. Second, a lower limit was placed on h_c of 2.0 $W/m^2.K$. This was done to ensure that the convective coefficient does not become too small, and reflects the uncertainty of the data at low wind speeds on the windward side, and the fact that on the leeward side the convective coefficient seemed to be almost constant below about 2 m/s (at about 3.5 $W/m^2.K$).

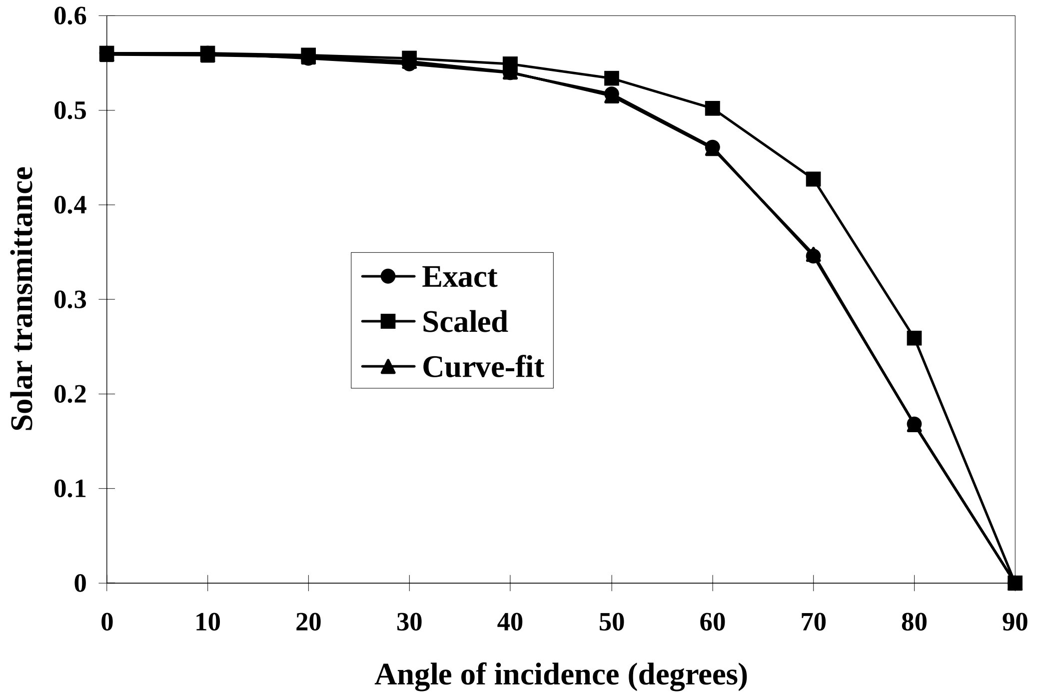

Figure 1. Solar transmittance for a low-emissivity high-transmittance double glazing. The curve labelled 'Exact' is obtained from Window 4.1. The curve labelled 'Curve-fit' is obtained from (1). The curve labelled 'Scaled' is obtained by using the clear single glazing transmittance scaled to agree with the exact value at zero angle of incidence.

Treatment of window frames

Even the simplest window frames are geometrically quite complex. The Frame 3.1 program (Enermodal Engineering, 1993), which can handle two-dimensional heat flows in window frames, was used to calculate frame *U*-values for a given set of conditions. The overall *U*-value of the glazing system is then calculated by taking an area-weighted average of the frame and glazing *U*-values, using a frame area fraction suitable for typical window sizes. One approximation involved in this treatment is that the thermal capacitance of the frame is not taken into account, i.e. it is treated as a pure resistance. However the total thermal capacitance of glazing frames is small compared to the capacitance of the rest of the building.

Window frames absorb solar energy, some of which is conducted indoors. The radiation absorbed on the outdoor surface is calculated as a function of the surface absorptance and angle of incidence. The fraction conducted indoors is calculated from the thermal resistance of the frame and the indoor and outdoor heat transfer coefficients.

Handling time-varying U-values

Time-varying *U*-values present a problem for the simulation engine, because strictly speaking all thermophysical properties must be constant in time. The problem was handled as follows. Glazing and frame *U*-values are calculated for a set of conditions that are roughly representative of “average” conditions in Australia, called “National Average Conditions” (NAC). The glazing system *U*-value at the NAC is then included in the fixed thermal network that represents the building, which is used to calculate zone response factors. At each hour, the actual surface heat transfer coefficients and hence the overall glazing system *U*-value are calculated. The difference between this *U*-value and the NAC *U*-value is used to calculate a correction heat flow, which is then applied to the zone containing the glazing.

This approach presented an unexpected difficulty when it was applied to the calculation of frame *U*-values. The overall *U*-value of the frame should be calculated at each hour for the particular values of the surface coefficients, but it is clearly impractical to use a program such as Frame 3.1 at each hour to do this. It was thought that the frame *U*-value could be adjusted at each hour according to the actual values of the surface coefficients at that time, as is done for the glass. However, this was not possible because of the fin effect of the frame. For example, for a particular unbroken aluminium frame with an indoor coefficient of 8.3 W/m^2.K and an outdoor coefficient of 11.3 W/m^2.K, the overall *U*-value was found to be 12.7 W/m^2.K. This is much larger than the value that would be obtained from the surface coefficients assuming one-dimensional heat flow. If at some particular time the surface coefficients are very different from these values, then it is not possible to deduce the *U*-value of the frame by subtracting the resistances corresponding to the original pair of coefficients and adding the resistances corresponding to the new pair. If this is attempted then very large or even negative *U*-values can result. This problem has not yet been solved, and in the current version the frame *U*-value is not adjusted at each hour, but remains at the value calculated at NAC.

MODELLING CONCRETE SLAB-ON-GROUND CONSTRUCTION

Heat flow through most building elements (walls, windows, and so on) is one-dimensional, that is, perpendicular to the surface. Given the areas and thicknesses that are typical of building materials, this is a reasonably good assumption. However, heat flow between indoors and outdoors via a concrete slab floor and the ground is clearly two-dimensional at best, and often must be considered to be three-dimensional. As buildings become better insulated, this heat flow path becomes increasingly important. For situations where the thermal performance is dominated by the building envelope, such as in houses, it is imperative that simulation programs deal with the floor-ground heat flow path reasonably accurately.

The slab-on-ground model in CHEETAH is based on the work of Muncey and Spencer (1978), and simply represents the ground as a resistance with a distributed capacitance connecting the indoor and outdoor temperatures. Typical values for a small house are R = 1.8 m^2.K/W and C = 4000 kJ/m^2.K. An improved model was developed by Delsante *et al*. (1983) and Delsante (1988, 1990). This section describes some further improvements in this model, which have been implemented in the NatHERS software.

The basic equations

The improved model is based on analytical solutions of two and three-dimensional slab/ground heat transfer for a simplified geometry. The ground is considered to be a semi-infinite solid, and surface temperatures T_i and T_o are applied to indoors to outdoors respectively. Fig. 2 shows the temperature profile at the surface; for clarity it is shown in its two-dimensional version, with a building of breadth *B* and wall of thickness *W*. Two cases are distinguished: the steady state, in which the temperatures shown in Fig. 2 are mean temperatures, calculated over a period of at least one year; and the transient state, in which the temperatures in Fig. 2 are to be interpreted as temperature *amplitudes*, with an assumed sinusoidal time dependence. In both cases the indoor temperature (mean or amplitude) is assumed to change linearly from its indoor value to its outdoor value over a distance equal to the wall thickness. Because the diffusion equation for heat flow is linear, the overall solution for a particular set of indoor and outdoor conditions can be obtained by addition of the steady-state solution and the transient solutions for any number of desired frequencies.

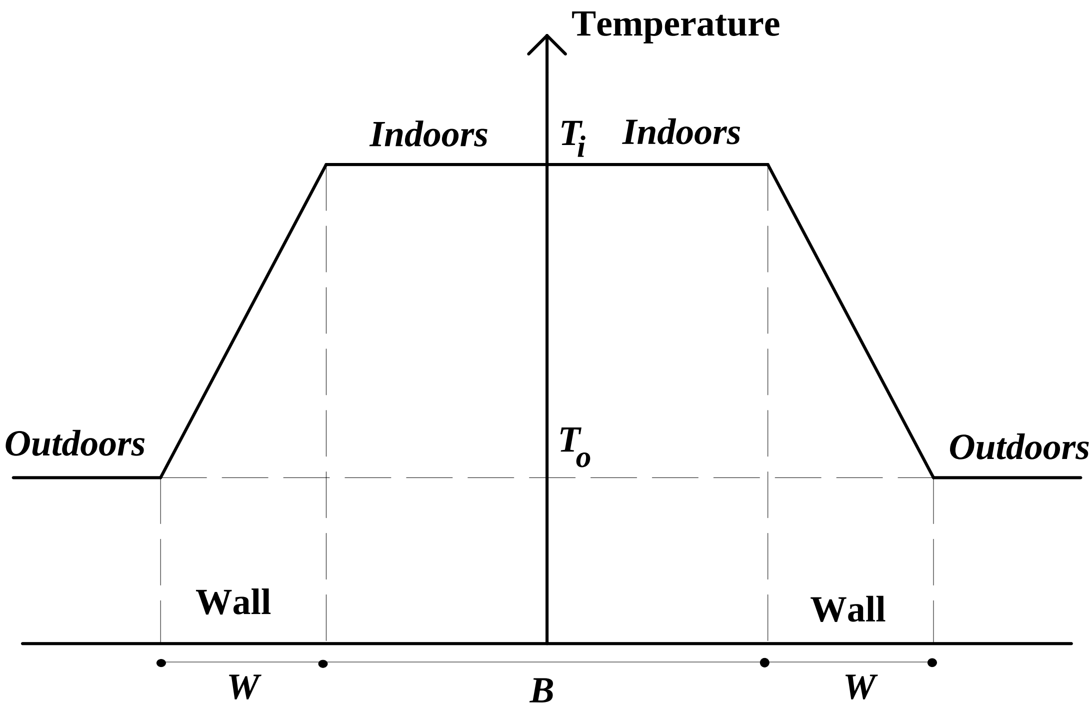

Figure 2. Two-dimensional version of the geometry used to develop the equations for the ground model. The building breadth is B, and the wall thickness is W. The indoor temperature is T_i and the outdoor temperature is T_o. In the steady state these are mean temperatures; in the transient state they are temperature amplitudes at a given frequency. The indoor temperature is assumed to change linearly from its indoor value to its outdoor value over a distance equal to the wall thickness.

Consider a rectangular floor of length *L* and breadth *B*, with a wall thickness *W*, laid on soil with thermal conductivity *k* and diffusivity κ, with a temperature profile as described above. Let *Q* be the total heat flow from the floor. Delsante *et al*. (1982) gave a 17-term expression for *Q* at steady state, which need not be quoted here. An excellent and more general approximation was found by Davies (1993a, 1993b) in terms of the floor area and perimeter:

$$Q = \frac{kP\left(T_i - T_o\right)}{\pi}\left[\ln(1+x) + x\ln(1+1/x)\right], \qquad (4)$$

where $x = 2A/(WP)$, and *A* is the area and *P* the perimeter. This is the recommended equation for the steady state.

For non-steady state, with sinusoidal indoor and outdoor temperatures, Delsante *et al.* (1982) gave the following approximate expression for the heat flow amplitude, $\tilde{Q}$:

$$\tilde{Q} = \frac{k(\tilde{T}_i - \tilde{T}_o)P}{\pi \alpha W}\left[\pi/4 - Ki_1(\alpha W) + Ki_3(\alpha W)\right] + k\alpha A\tilde{T}_i\,, \tag{5}$$

where $\tilde{T}_i$ and $\tilde{T}_o$ are the indoor and outdoor temperature amplitudes (including a phase term if necessary), $\alpha = \left(j\Omega / \kappa\right)^{1/2}$, Ω is the assumed frequency, $j = \sqrt{-1}$, and Ki_1 and Ki_3 are the repeated integrals of the modified Bessel function K_0 (see Delsante *et al*. (1982) for details).

The frequency response of the building is first calculated over the range of frequencies for which the response is non-zero. In order to obtain acceptable accuracy with this ground model, it was necessary to sample the frequency response at 59 frequencies, given by $(2\pi/24).2^{(n-39)/2}$ (n = 1,2,....,59) radians per hour. Because the initial frequency is so low, it was found that the expression (5) for the ground frequency response was not valid at this and similar frequencies. The following procedure was adopted to obtain a better estimate at low frequencies. The exact two-dimensional result for a building of breadth B and length L was given by Delsante *et al*. (1982) as

$$\tilde{Q} = \frac{2Lk(\tilde{T}_i - \tilde{T}_o)}{\pi \alpha W}\left[\pi / 4 - Ki_1(\alpha W) + Ki_3(\alpha W) - Ki_1(\alpha B) + Ki_3(\alpha B)\right.$$
$$\left. + Ki_1(\alpha(B+W)) - Ki_3(\alpha(B+W))\right] + k\alpha LB\tilde{T}_i\,. \tag{6}$$

Equation (5) had been obtained from (6) by replacing $2L$ by P and LB by A, and noting that the sums of the Ki terms in B and $B+W$ are negligible for frequencies not too close to zero. However, (5) eventually diverges as the frequency approaches zero, whereas (6) gives the correct steady-state result. Thus a better estimate for the three-dimensional result at low frequencies is to adopt Davies' procedure and replace B in (6) by the characteristic length $LB/(L+B)$, or in general $2A/P$, giving

$$\tilde{Q} = \frac{k(\tilde{T}_i - \tilde{T}_o)P}{\pi \alpha W}\left[\pi/4 - Ki_1(\alpha W) + Ki_3(\alpha W) - Ki_1(2A\alpha / P) + Ki_3(2A\alpha / P)\right.$$
$$\left. + Ki_1(\alpha(2A/P+W)) - Ki_3(\alpha(2A/P+W))\right] + k\alpha A\tilde{T}_i\,. \tag{7}$$

This expression does not diverge at low frequencies, and in fact yields Davies' approximation (4) to the steady-state result in the zero-frequency limit.

Comparison with a numerical study: steady state

The equations described above have already been successfully compared with measurements of heat flow from the slab floor of a real building (Delsante, 1990). Another comparison can be made with the work of Bahnfleth and Pederson (1990) who developed an hourly three-dimensional finite-difference model of heat transfer from slab-on-ground floors. Unfortunately some of their assumptions are not quite clear, although it appears that their calculation does not specify a wall thickness; the implication is that the temperature changes discontinuously from its indoor to its outdoor value. This differs from the model described above, where the wall thickness is used to allow the temperature to change continuously from its indoor value to its outdoor value over a finite distance. As well, it appears that the slab (0.1 m thick) is placed on the surface of the ground, so that the floor is higher than the ground level by 0.1 m. In contrast, the Delsante model assumes, for reasons of geometrical simplicity, that the floor is at ground level. While there are differences in assumptions between the models, they are sufficiently close that a comparison is worthwhile.

Bahnfleth and Pederson note that the *ASHRAE Fundamentals* handbook (ASHRAE, 1993) gives the following expression for heat loss per unit area from a slab floor:

$$Q = F_2(P / A)\Delta T\,, \tag{8}$$

where P is the floor perimeter, A its area, ΔT the indoor-outdoor design temperature difference, and F_2 is a tabulated function of construction type and climate. This equation implies that for a given construction type and climate, the heat loss per unit area (or the U-value) depends linearly on the ratio of perimeter to area. Bahnfleth and Pederson examined a wide range of floor sizes (ranging from 144 m^2 to 3600 m^2) and concluded that the heat loss per unit area is not linearly dependent on P/A, in contradiction to (8). They fitted their results empirically to the form

$$Q = c_1 (P / A)^{d_1} \tag{9}$$

where c_1 and d_1 are climate-dependent constants, and where d_1 was found to be less than 1.0 (typically 0.75). This conclusion agrees qualitatively with equation (4), since it can be re-written as

$$Q = (kP / \pi A)\left[\ln(1+x) + x\ln(1+1/x)\right], \tag{10}$$

which implies that Q is less than linearly dependent on P/A (since $x = 2A/WP$). The advantage of using (10) is that it explicitly shows the dependence of Q on all parameters, whereas (9), since it represents an empirical curve-fit to numerical results, requiring the re-calculation of c_1 and d_1 for each case, does not give any insight into the functional form of the heat loss.

Having established a qualitative agreement in the functional form, more detailed comparisons were then undertaken for the heat loss. In particular, Bahnfleth and Pederson found that the steady-state heat loss was not proportional to the soil conductivity, whereas (10) indicates that it is. The reason for this is that while Bahnfleth and Pederson varied the soil conductivity from 0.5 to 2.0 W/m.K, they kept the slab conductivity constant at 0.93 W/m.K. Since heat from indoors flows first through the slab and then through the soil, one would not expect the heat loss to be strictly proportional to the soil conductivity. The fact that in their geometry the vertical slab edges are (presumably) exposed to outdoor air would tend to exacerbate this effect. Furthermore, Bahnfleth and Pederson used a fixed indoor surface heat transfer coefficient of 6.13 W/m^2.K, which would also reduce the sensitivity to soil conductivity. Thus the fixed surface coefficient and slab resistance must be taken into account in the Delsante model in order to undertake a fair comparison.

A straightforward way of doing this is to recognise that (10) gives the U-value of the ground only. The overall U-value is obtained by adding the resistance of the ground to the surface and slab resistance. The surface resistance given by Bahnfleth and Pederson is 0.163 m^2.K/W, while the slab resistance is 0.108 m^2.K/W. Combining this with (10) gives the following expression for the overall U-value:

$$U = \left[0.271 + \frac{\pi A}{kP}\left[\ln(1+x) + x\ln(1+1/x)\right]^{-1}\right]^{-1}. \tag{11}$$

Equation (11) was compared with the results of Bahnfleth and Pederson for various square and rectangular floors, for three values of soil conductivity: 0.5, 1.0 and 2.0 W/m.K. A wall thickness of 0.2 m was assumed. The results are given in Table 1.

Table 1. Comparison of steady-state component of Delsante's analytical model with Bahnfleth and Pederson's numerical model.

L x B (m)	**Soil *k* (W/m.K)**	***U*-value (eq. (11)) (W/m^2.K)**	***U*-value (Bahnfleth and Pederson) (W/m^2.K)**	**Difference in *U*-value (%)**	**Ratio to *U*-value for *k* =1 (eq. (11))**	**Ratio to *U*-value for *k* =1 (Bahnfleth and Pederson)**
12x12	0.5	0.220	0.268	-17.9	0.529	0.618
"	1.0	0.416	0.434	-4.1	1.000	1.000
"	2.0	0.748	0.681	9.8	1.798	1.569
6x24	0.5	0.259	0.324	-20.6	0.535	0.622
"	1.0	0.484	0.521	-7.1	1.000	1.000

"	2.0	0.856	0.808	5.9	1.769	1.689
45x45	0.5	0.079	0.097	-18.6	0.510	0.584
"	1.0	0.155	0.166	-6.6	1.000	1.000
"	2.0	0.298	0.277	7.6	1.923	1.669
18x112	0.5	0.107	0.128	-16.4	0.514	0.590
"	1.0	0.208	0.217	-4.1	1.000	1.000
"	2.0	0.393	0.358	9.8	1.889	1.650

The pattern of differences in column 5 suggest that agreement is best for a conductivity between 1.0 and 2.0 W/m.K. For a conductivity of 1.0 (which is the value closest to that of the concrete slab) the Delsante model consistently gives a slightly lower heat loss than the Bahnfleth and Pederson calculations, by between 4% and 7%. This might be because the Delsante model does not take into account the effect of the raised slab, which would be expected to increase the heat loss. The sensitivity to soil conductivity is shown in the last two columns of Table 1, and is clearly stronger for the *U*-value calculated from (11) (note that a strict linear dependence would give ratios of 0.5, 1.0 and 2.0 respectively for the three values of conductivity).

Comparison with a numerical study: time-dependent

Equation (7) was compared with the time-dependent heat flows calculated by Bahnfleth and Pederson. In their calculations, the indoor temperature was constant. Hence $\tilde{T}_i$ is zero and so (7) predicts that the heat flow per unit area is proportional to *P/A*. As they did for the steady-state calculations, Bahnfleth and Pederson fitted their non-steady-state results to the form

$$\tilde{Q} = c_2 (P/A)^{d_2} (\tilde{T}_i - \tilde{T}_o) \exp(-j\Omega\phi), \qquad (12)$$

where c_2 and d_2 are the curve-fit constants and ϕ is a phase angle. They calculated the constants for four climates and found d_2 values of 0.999, 0.999, 0.995 and 0.997 respectively. Thus their results also predict a linear dependence on *P/A*. The dependence of the new model on soil conductivity, diffusivity and floor dimensions was then compared with the results of Bahnfleth and Pederson, for the same floors as used in Table 1. The results are given in Table 2, which gives the modulus of $\tilde{Q}/(T_i - T_o)$ for a frequency corresponding to the annual cycle.

As was found for the steady-state comparisons, the new model is more sensitive to soil conductivity than Bahnfleth and Pederson’s calculations, and agreement is best for a soil conductivity somewhat greater than 1.0 W/m.K. Since typical soil conductivities are usually taken to be about 1.4 W/m.K (e.g. CIBS Guide A3, 1980), Table 2 suggests that for this value the Delsante model and Bahnfleth and Pederson's calculations would be in very good agreement for a wide range of floor sizes. The sensitivity to diffusivity is very similar for the two models, as can be seen by taking heat flow ratios for two different diffusivities at a fixed conductivity.

Table 2. Comparison of non-steady-state component of the new model (equation (7)) with Bahnfleth and Pederson's numerical model, for a frequency corresponding to the annual cycle. *k* is the assumed soil conductivity, and κ the diffusivity.

LxB (m)	Soil *k* (W/m.K)	Soil κ (x 10^7 m^2/s)	Heat flow amplitude (eq. (7)) (W/m^2.K)	Heat flow amplitude (Bahnfleth and Pederson) (W/m^2.K)	Difference in amplitudes (%)
12x12	2.0	8.9	0.4185	0.3885	7.7
"	2.0	6.9	0.3939	0.3675	7.2
"	1.0	6.9	0.2270	0.2564	-11.5
"	1.0	3.5	0.1933	0.2262	-14.5
"	0.5	3.5	0.1060	0.1532	-30.8
6x24	2.0	8.9	0.5098	0.4846	5.2
"	2.0	6.9	0.4806	0.4586	4.8
"	1.0	6.9	0.2797	0.3201	-12.6
"	1.0	3.5	0.2388	0.2822	-15.4
"	0.5	3.5	0.1316	0.1913	-31.2
45x45	2.0	8.9	0.1208	0.1048	15.3
"	2.0	6.9	0.1130	0.0991	14.0
"	1.0	6.9	0.0632	0.0688	-8.1
"	1.0	3.5	0.0534	0.0610	-12.5
"	0.5	3.5	0.0288	0.0410	-29.8
18x112	2.0	8.9	0.1730	0.1516	14.1
"	2.0	6.9	0.1620	0.1433	13.0
"	1.0	6.9	0.0910	0.0997	-8.7
"	1.0	3.5	0.0770	0.0883	-12.8
"	0.5	3.5	0.0417	0.0594	-29.8

CONCLUSION

The Nationwide House Energy Rating Scheme is still under development, as is the software that underpins it. This paper has given an overview of the current version of the software, and has described the improvements to the glazing model and the modelling of heat transfer between a concrete slab floor and the ground that were undertaken.

Some aspects of the scheme and the software will need to be developed further. One of the most important is the rating of buildings in warm-humid or hot-humid climates. In many cases houses there do not have air conditioning, relying instead on good ventilation, shading, and ceiling fans. Thus it may be more realistic to rate houses on the basis of indoor conditions in the absence of air conditioning, rather than cooling energy requirements. This would require the calculation of a comfort index (rather than the environmental temperature which is currently calculated) and the incorporation of a suitable model for calculating ventilation rates in multi-zone buildings with large openings, as a function of indoor and outdoor temperatures, wind speed and wind direction. These improvements are currently in the planning stage.

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