COMPARISON OF THE PERIODIC SOLUTION METHOD WITH TRNSYS AND SUNCODE FOR THERMAL BUILDING SIMULATION

N. K. BANSAL[†] and M. S. BHANDARI
Centre for Energy Studies, Indian Institute of Technology, Hauz Khas, New Delhi 110 016, India

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Abstract—Based on periodic solutions of the governing heat conduction equations in a single zone building, computer software ADMIT has been developed for thermal simulation of buildings. Standard computer software, namely TRNSYS and SUNCODE, have also been used to simulate the same building under similar conditions. Simulations have been performed for three different climatic zones in India for light and heavy constructions under conditions of glazed/unglazed areas and ventilation rates. The results are presented in terms of the hourly variation of the room temperature. For insulated heavy construction, the results of different models are significantly different. This difference is due to the use of different approaches to solve the heat conduction equations. SUNCODE depends on the RC network approach and underestimates the heat losses. TRNSYS uses the transfer function approach, which is sensitive to the initially assumed value of the room temperature. ADMIT represents a quasi-steady-state periodic variation and is not suitable for transient variations. For insulated light buildings, the heat transfer mechanisms used in the mathematical models are not the governing factors. The models also differ in treating the penetration of solar radiation through a glazed window and the subsequent heat-transfer mechanism. For a south window and air changes in an insulated building, the results obtained by SUNCODE and ADMIT are in good agreement, but the results obtained by TRNSYS are considerably different. The reason for this needs detailed analysis.

1. INTRODUCTION

Building simulation, from the point of view of calculating energy consumption for heating and/or cooling of buildings, has been of much interest in recent years. Task XIII of the International Energy Agency (IEA), with the aim of incorporating innovative materials, uses computer models to investigate the impact of advanced solar techniques on energy performance and thermal comfort in building design, components or systems in an advanced design (Eigdems, 1993). It was, however, found that most of these techniques cannot be directly modelled by the available simulation programs. The IEA task group, therefore, concentrated on a comparison of simulation models based on the calculation results of four typical cases and on composing information sets with regard to the modelling of the above-mentioned advanced technologies (Poel, 1993). The authors have been working with TRNSYS (1990) and SUNCODE (1985) for the past two years. It is found that modification of the existing codes needs a thorough understanding of several mathematical techniques, which is highly time consuming. In order to develop software where it is easy to incorporate several techniques of heating and/or cooling, the authors have used the periodic solution technique of the governing heat conduction equations, resulting in closed-form solutions. The authors had the flexibility of incorporating many passive concepts, especially for cooling, which are not yet available in the majority of the software. The results of the technique presented here are compared with the corresponding results obtained from TRNSYS and SUNCODE for light and heavy constructions and for different alternatives of physical, as well as climatic, parameters.

2. MATHEMATICAL MODEL

2.1. *Periodic solution*

Heat transferred into a building can be assumed to be governed by the one-dimensional heat conduction equation:

$$k\frac{\partial^2 T(x,t)}{\partial x^2} = \rho C\frac{\partial T(x,t)}{\partial t}. \tag{1}$$

This has to be solved for various walls, roof and ground which are essentially flat geometries. Corresponding to Fig. 1, the boundary conditions, which have to be satisfied by the solution of eqn (1), are

$$-k\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=0} = q_o \tag{2a}$$

$$-k\left.\frac{\partial T(x,t)}{\partial x}\right|_{x=L} = q_R. \tag{2b}$$

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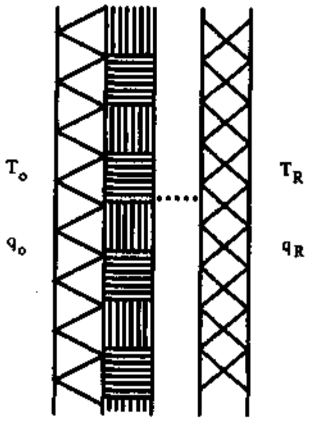


Fig. 1. Heat transfer into a building element.

All time-varying functions, like solar radiation and ambient temperature, can be expressed in terms of a Fourier series, namely

$$f(t) = \sum_{n=-\infty}^{+\infty} f_n \exp(in\omega t) \tag{3}$$

where ω corresponds to the frequency of variation, i.e. $\omega = 2\pi/T_p$; T_p is the period of variation. For the nth harmonic of the temperatures T_{on} and T_{Rn} on the opposite sides of a composite wall, Pipes (1958) has shown that the temperature and energy cycles can be related to each other by the following matrix equation:

$$\begin{bmatrix} T_{Rn} \\ q_{Rn} \end{bmatrix} = \begin{bmatrix} 1 & -R_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} B_{1n} & C_{1n} \\ D_{1n} & B_{1n} \end{bmatrix} \times \begin{bmatrix} B_{2n} & C_{2n} \\ D_{2n} & B_{2n} \end{bmatrix} \cdots \begin{bmatrix} 1 & -R_o \\ 0 & 1 \end{bmatrix} \begin{bmatrix} T_{on} \\ q_{on} \end{bmatrix} \tag{4}$$

where B_{in}, C_{in} and D_{in} ($i = 1$ to m) correspond to the mth layer in the wall/roof and are given by:

$$B_{mn} = \cosh[(1+i)\alpha_{mn}L_m] \tag{5}$$

$$C_{mn} = \frac{\sinh[(1+i)\alpha_{mn}L_m]}{k_m(1+i)\alpha_{mn}} \tag{6}$$

$$D_{mn} = -k_m(1+i)\alpha_{mn}\sinh[(1+i)\alpha_{mn}L_m] \tag{7}$$

$$\alpha_{mn} = \left(\frac{n\omega\rho_m C_m}{2k_m}\right)^{1/2}. \tag{8}$$

Equation (4) can be written in the following form

$$\begin{bmatrix} T_{Rn} \\ q_{Rn} \end{bmatrix} = \begin{bmatrix} 1 & -R_i \\ 0 & 1 \end{bmatrix} \begin{bmatrix} B_n & C_n \\ D_n & E_n \end{bmatrix} \times \begin{bmatrix} 1 & -R_o \\ 0 & 1 \end{bmatrix} \begin{bmatrix} T_{on} \\ q_{on} \end{bmatrix} \tag{9}$$

$$= \begin{bmatrix} P_n & Q_n \\ R_n & S_n \end{bmatrix} \begin{bmatrix} T_{on} \\ q_{on} \end{bmatrix} \tag{10}$$

$$S_n = R_o D_n + B_n \tag{11}$$

and

$$Q_n = -R_i E_n + C_n + R_1 R_o D_n - R_o B_n \tag{12}$$

where R_o, R_i are the surface film resistances, namely $R_o = 1/h_o$ and $R_i = 1/h_i$.

Solving the matrix eqn (10), the nth harmonic of the heat flux entering through a multilayered wall is written in terms of the temperatures on its two sides as:

$$q_{Rn} = \frac{S_n T_{Rn} - T_{on}}{Q_n}. \tag{13}$$

For the surface facing the ground, heat transfer is considered into a semi-infinite medium, R_o is replaced by

$$\frac{1}{k_G(1+i)\alpha_{Gn}}$$

and $T_{on} = 0.0$.

In reality, the wall/roof and the floor receive solar radiation either on the external surface or on the internal (through a window) or on both. Its effect is incorporated into the above equations and the various heat gains through the corresponding walls/roof are obtained as given below:

(1) The heat flux transmitted through the wall and roof is expressed as:

$$Q = A_{WL} \sum_{n=-\infty}^{+\infty} \times \frac{S_n\left(T_{Rn} + \frac{\alpha_i I_{iwn}}{h_i}\right) - \left(T_{an} + \frac{\alpha_0 I_{on}}{h_0}\right)}{Q_n} \times \exp(in\omega t) + A_{WL} \sum_{n=-\infty}^{+\infty} (\alpha_i I_{iwn}) \exp(in\omega t) \tag{14}$$

where A_{WL} is wall/roof area, I_{iw} and I_o are radiation incident on inside and outside surfaces respectively, n denotes the nth harmonic, S_n and Q_n depend upon the thermophysical properties of walls or roof materials, h_i and h_o are the inside and outside convective heat-transfer coefficients respectively, α_i and α_o are absorptivities of inner and outer surfaces respectively and ω is the angular frequency.

(2) The energy flux through the floor is obtained by:

$$Q = A_F \sum_{n=-\infty}^{+\infty} \frac{S_n\left(T_{Rn} + \frac{\alpha_i I_{ifn}}{h_i}\right)}{Q_n} \exp(in\omega t) + A_F \sum_{n=-\infty}^{+\infty} (\alpha_i I_{ifn}) \exp(in\omega t) \qquad (15)$$

where A_F is the area of the floor and I_{if} is the radiation incident on the floor.

(3) Direct gain through the window is calculated every hour and its effect on the indoor air temperature is calculated by assuming that 60% of the radiation is absorbed by the floor and 8% is absorbed by each of the four walls and the ceiling.

(4) The heat gain due to infiltration of air from the ambient into the room is calculated from the relation

$$Q = C_{inf} \sum_{n=-\infty}^{+\infty} (T_{an} - T_{Rn}) \exp(in\omega t) \qquad (16)$$

where C_{inf} is the infiltration coefficient.

(5) The expression for ventilation heat gain is given by:

$$Q = \sum_{n=-\infty}^{+\infty} C_v (T_{an} - T_{Rn}) \exp(in\omega t) = \sum_{n=-\infty}^{+\infty} \sum_{m=-\infty}^{+\infty} C_{vm} (T_{an} - T_{Rn}) \exp[i(n+m)\omega t] \qquad (17)$$

where the ventilation term C_v is assumed to be time dependent and is expressed in terms of the Fourier coefficient by:

$$C_v = \sum_{m=-\infty}^{+\infty} C_{vm} \exp(in\omega t).$$

(6) Heat transmission through the window glass and the door is expressed in terms of their respectives U values by:

$$Q = A_{WN} U \sum_{n=-\infty}^{+\infty} (T_{an} - T_{Rn}) \exp(in\omega t) \qquad (18)$$

where A_{WN} is the area of the window and U is the overall heat-transfer coefficient.

(7) For the case when two rooms are adjacent to each other, heat transfer through the separating wall (internal wall) is determined by the characteristics of the wall and is given by:

$$Q = A^i_{WL} \sum_{n=-\infty}^{n=+\infty} \frac{S_n T_{Rn} - T_{R2n}}{Q_n} \exp(in\omega t). \qquad (19)$$

Room air temperature is essentially determined by the net amount of heat gain/loss by the room air through the building components. The same is given below, in the form of an energy balance equation given by:

$$M_r C_p \frac{d}{dt}\left[\sum_{n=-\infty}^{+\infty} T_{Rn} \exp(in\omega t)\right] = \sum_j Q_j \qquad (20)$$

where M_r is the thermal mass of room air, C_p is the specific heat (J/kg K) and j corresponds to eqns (14)–(19). The choice about the use of number of harmonics usually depends upon the variation of the input parameters, i.e. ambient temperature and solar radiation. For smoothly varying inputs, even two harmonics, $n = -2$ to $+2$, are sufficient. For fluctuating inputs six harmonics, $n = -6$ to $+6$, are found to be adequate. For $n = 6$ and $n = 7$, the results show a difference of ±0.001°C. Harmonics from $n = -6$ to $+6$ are, therefore, considered and compared with coefficient of equal n. Equation (20) gives 13 equations which can be written in the form of a matrix equation given by:

$$[X]_{13\times 13}[T_{Rn}]_{13\times 1} = [Y]_{13\times 1} \qquad (21)$$

or

$$[T_{Rn}]_{13\times 1} = [X]^{-1}_{13\times 13}[Y]_{13\times 1}.$$

Solution of eqn (21) determines the different harmonic components of the room air temperature and these are combined to give the hourly variation of the room air temperature.

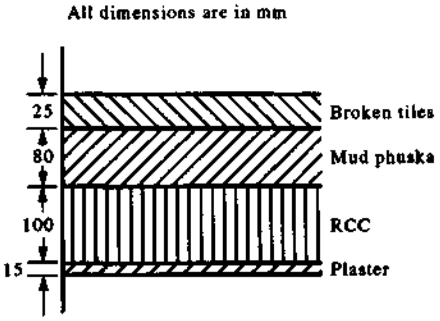
TRNSYS and SUNCODE are essentially modelled with the same type of heat balances. The difference lies in the method of solving the heat conduction equations. In TRNSYS, the walls/roof are modelled according to the transfer function relationship of Mitlas and Arseneault (1971) evaluated numerically at equal time intervals. In SUNCODE the thermal response of walls is calculated by approximating the wall construction with a thermal netowrk. This network is solved using the explicit finite difference or Euler's method. The program uses a central air temperature node for each zone defined by the user. The resulting air temperature is calculated at each time step by rewriting the energy balance equations.

3. RESULTS AND DISCUSSION

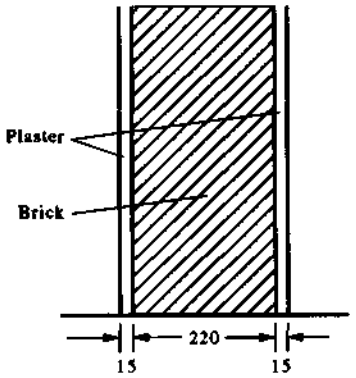
The calculations have been performed for a single zone building of two sizes: 4 × 4 × 3 m, and 6 × 4 × 3 m. The typical construction of roof and walls are given in Figs 2 and 3 for heavy and light construction, respectively; the thermophysical parameters used for the calculations are given in Table 1. The calculations have been performed for a representative day of all 12 months in three climatic zones of India (Bansal and Minke, 1988). The average climatic conditions of these three zones are given in Fig. 4. Additionally the following parametric variation is considered for the calculation:

(1) no window, no insulation, no ventilation (NWNI0)
(2) window, no insulation, no ventilation (WNI0)
(3) window, no insulation, five air changes per hour (WNI5)
(4) no window, insulation, five air changes per hour (NWI5)
(5) window, insulation, five air changes per hour (WI5).

For the case when a window is considered, it is assumed to be a part of the south wall and is 10% of the wall area. When insulation of 5 cm polystyrene is considered it is assumed to be placed on the inner surface of the walls/roof, i.e. facing the room. For the sake of brevity the results have been presented for the months of January and June (typical winter and summer months, respectively) only. Figures 5–7 show the variation of room air temperature for different parametric variations for Delhi, Jodhpur and Leh, respectively, for a room size of 4 × 4 × 3 m. Figure 8 shows the same for Delhi for a room size of 6 × 4 × 3 m.



Roof details



Wall detail

Fig. 2. Wall and roof details considered for a heavy construction single zone building.

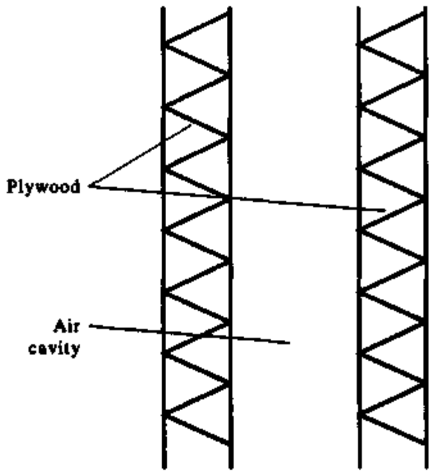


Fig. 3. Wall and roof details considered for a light construction single zone building.

Various effects can be seen in Fig. 5(a) and (b). For no window, no insulation and no air changes, hourly variation of the room air temperature calculated by (difference between the maximum and minimum temperatures) ADMIT shows the least fluctuations because this model is based on the quasi-steady-state periodic solution approach. SUNCODE, which is based on RC network theory, estimates lower heat losses and therefore yields highest values for the room temperature. TRNSYS, based on the transfer function approach, is very sensitive to the initially assumed value of the room temperature and also shows larger fluctuations than realized in practice. When a window is considered on the south wall, all the models yield higher temperatures, as expected, but the difference in the values of room temperatures between the three models is less than 2°C. Further consideration of five air changes per hour diminishes the difference still further. The difference between the calculated results using ADMIT, SUNCODE and TRNSYS never exceeds 1°C

Table 1. Thermophysical properties of different materials used for simulation

S no.	Material	Density (kg/m^{-3})	Specific heat (J/kg K)	Conductivity (W/m K)
1	brick	1820.0	880	0.81
2	plaster	1762.0	840	0.72
3	RCC	2280.0	880	1.58
4	mudphuska	1622.0	880	0.52
5	broken tiles	1820.0	880	0.81
6	insulation (expanded polystyrene)	34.0	1340	0.035
7	soil	1958.0	840	1.21
8	plywood	530.0	1300	0.138

except during the late hours, where TRNSYS still shows higher temperatures. While considering a window and air changes in an insulated house, ADMIT and SUNCODE yield nearly the same room temperatures, whereas the temperatures obtained by TRNSYS are significantly lower. TRNSYS is therefore very sensitive to ventilation/infiltration of the ambient air into the room.

For lighter construction, as expected, the fluctuations in the room air temperature are higher. The difference in the room temperature values calculated by TRNSYS and SUNCODE, in this case, is marginal because the low capacity effect does not significantly affect the way heat transfer is calculated. For no window, insulation and five air changes, for example, the difference between the results is always lower than 0·5°C. As soon as the window is considered, the results of TRNSYS differ considerably (by about 3°C) with the corresponding values of SUNCODE and ADMIT. Obviously there is a difference in the manner in which the incident radiation is handled in various models. ADMIT calculates the incident solar radiation on windows, its penetration into the room, further reflection and absorption by other surfaces, etc., which actually happens. TRNSYS does take into account the absorption of reflected radiation but in a global fashion by weighing over the respective areas. This suggests that the penetration of solar radiation through a window and its distribution onto various surfaces need further investigations to modify the algorithm in TRNSYS and also perhaps in SUNCODE.

Figure 6(a) and (b) shows the building's performance for the hot and dry zone during the summer for heavy and light construction, respectively. For no insulation and no ventilation, the fluctuations in the room temperature are higher for lighter buildings as expected and the indoor air temperatures are well above the ambient temperatures. Consideration of five changes of air brings down the temperature. Providing an internal insulation and keeping five air changes helps to keep the room temperature around the average ambient temperature, as predicted by ADMIT and SUNCODE. TRNSYS shows higher fluctuations. Considering a south window elevates the room temperatures, as predicted by ADMIT and SUNCODE, but the predictions by TRNSYS are still more optimistic, suggesting that TRNSYS needs to be investigated from the point of view of heat transfer and penetration of radiation through a window. Judkoff and Neymark (1995) corrected a bug in the transfer function (BID) module of TRNSYS causing insensitivity to thermal capacitance effects. In any case, all the models suggest that for hot and dry conditions, heavy construction with insulation on the external wall and avoiding a south glazed window is preferred for building construction.

Figure 7(a) and (b) shows the hourly variation of room air temperatures for cold and sunny climatic conditions. The trends of variation predicted by the models essentially remain the same. The overall physical behaviour is that the auxiliary heating and insulation of the buildings in these climatic conditions are necessary for thermal comfort. Lightweight construction with insulation behaves as good as a heavyweight building which is well insulated and possesses a window facing south.

As the single zone size is increased, the variations in the results obtained by ADMIT, SUNCODE and TRNSYS are essentially the same (Fig. 8).

4. CONCLUSIONS

Different models use different mathematical techniques and therefore the results of building simulation from each of these models differ for different construction techniques and they are

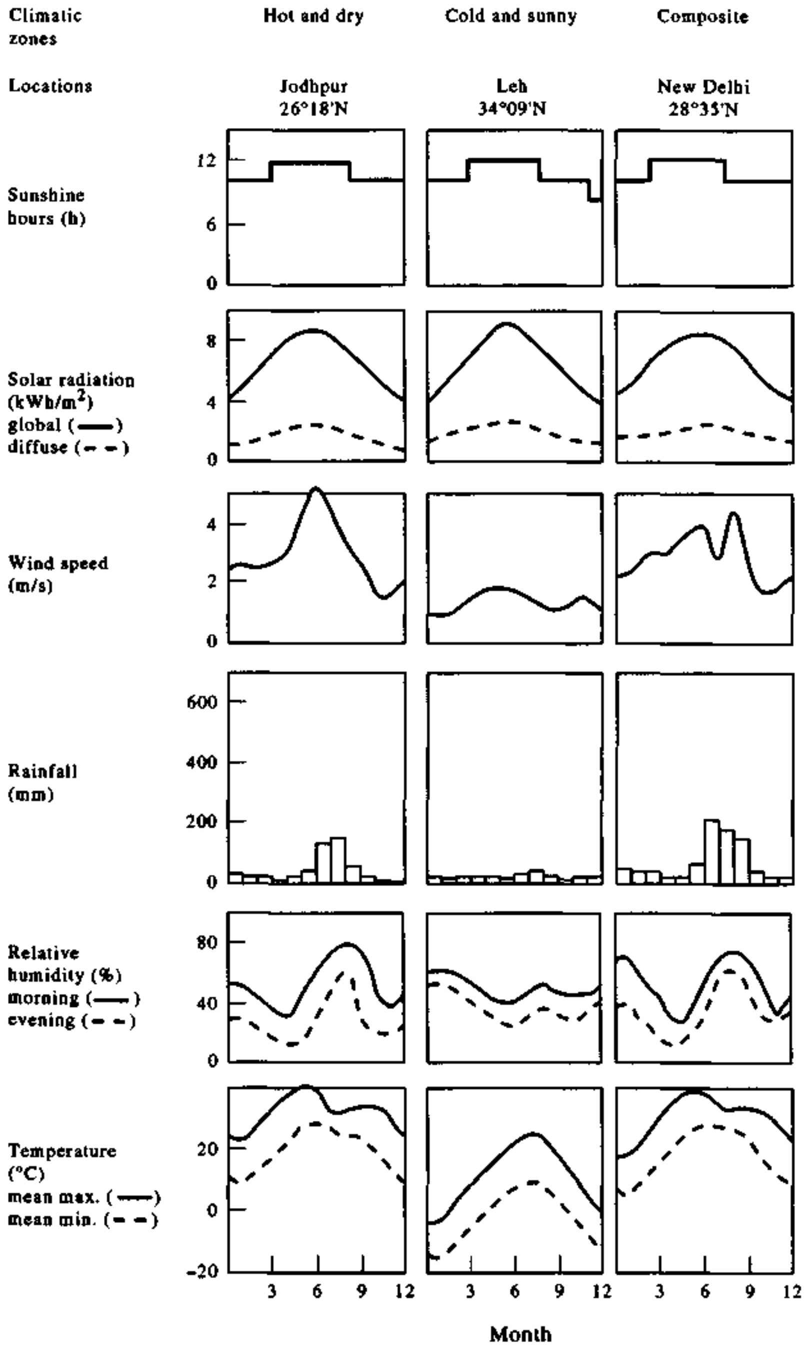


Fig. 4. Climatic data for Jodhpur, Leh and New Delhi representation of hot and dry, cold and sunny, and composite climatic conditions.

also sensitive to the climatic conditions. For the case of a light insulated building with no window, the results obtained from different models are in good agreement, whereas for heavy, multilayered walls/roof, the results are significantly different. SUNCODE underestimates the heat transfer (losses), while TRNSYS results are sensitive to the initially assumed indoor air temperature. All the three methods differ significantly in dealing with the radiation through a glazed window. Detailed comparative studies between simulation results and field measurements are essential for further research work. Moreover, incorporation of passive techniques, especially for cooling purposes, should be taken up for international use.

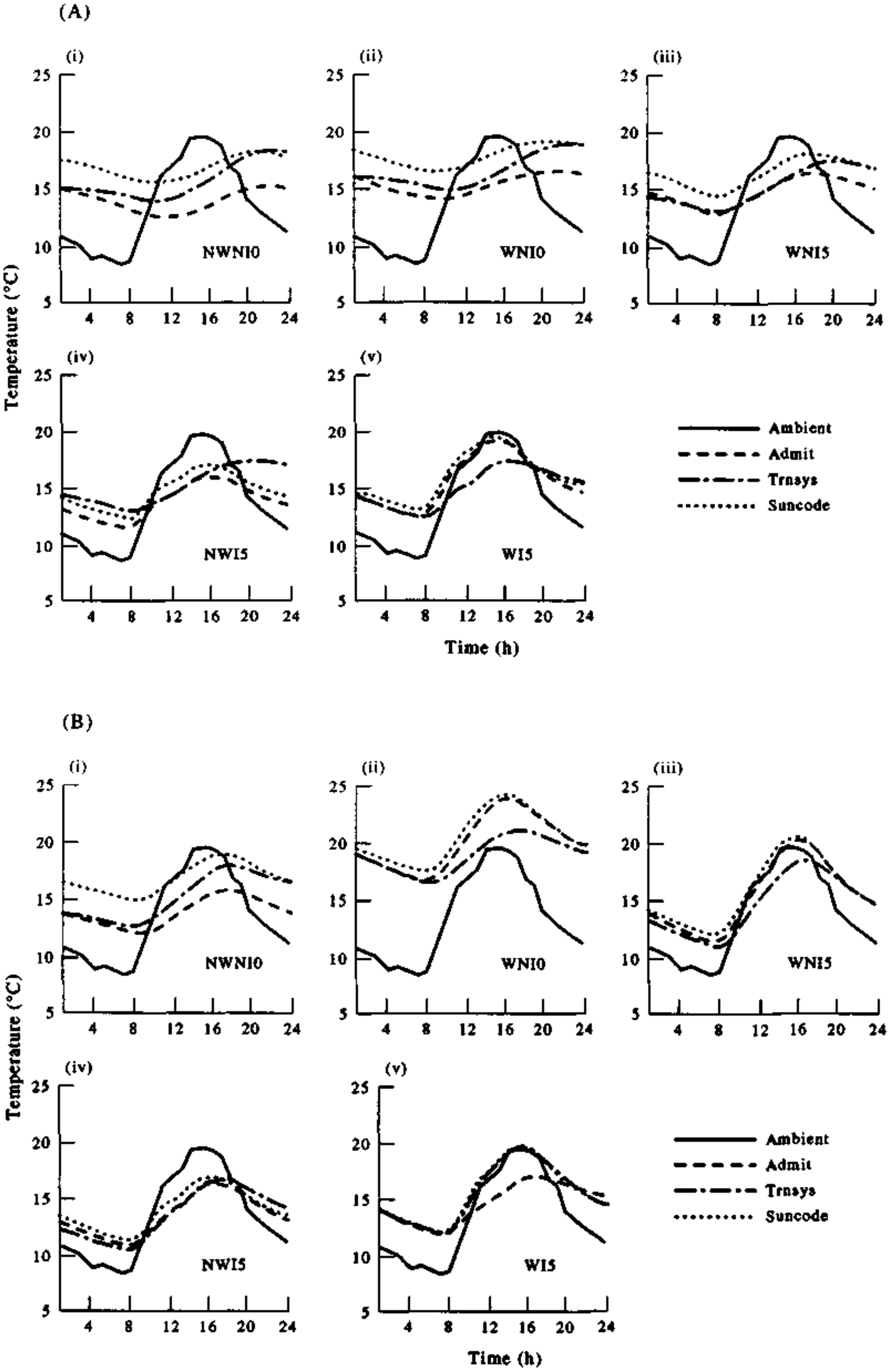


Fig. 5. Hourly variation of room temperature for Delhi in January for (a) heavy construction (room size 4 × 4 × 3 m), (b) light construction (room size 4 × 4 × 3 m).

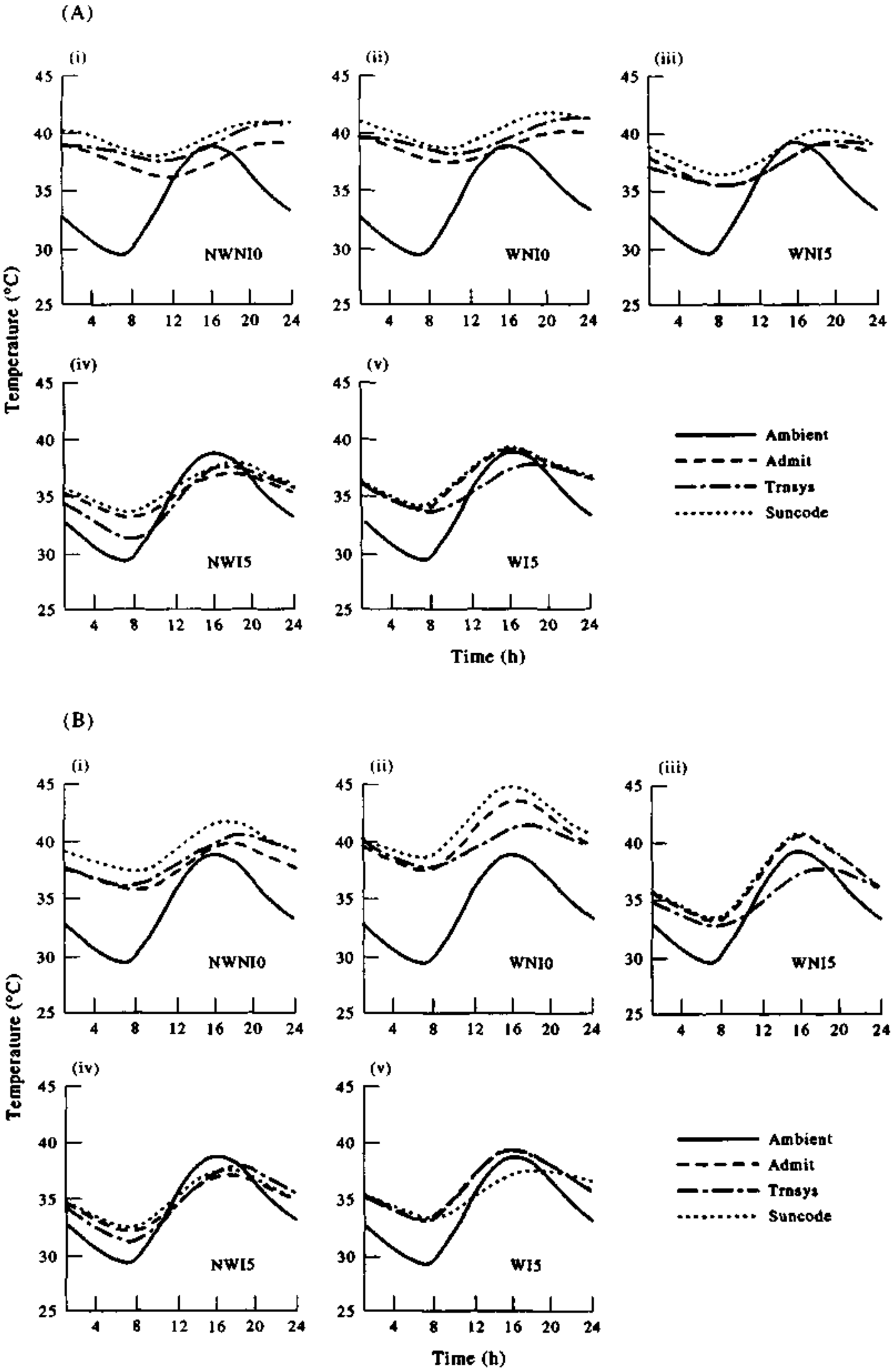


Fig. 6. Hourly variation of room temperature for Jodhpur in June for (a) heavy construction (room size 4 × 4 × 3 m), (b) light construction (room size 4 × 4 × 3 m).

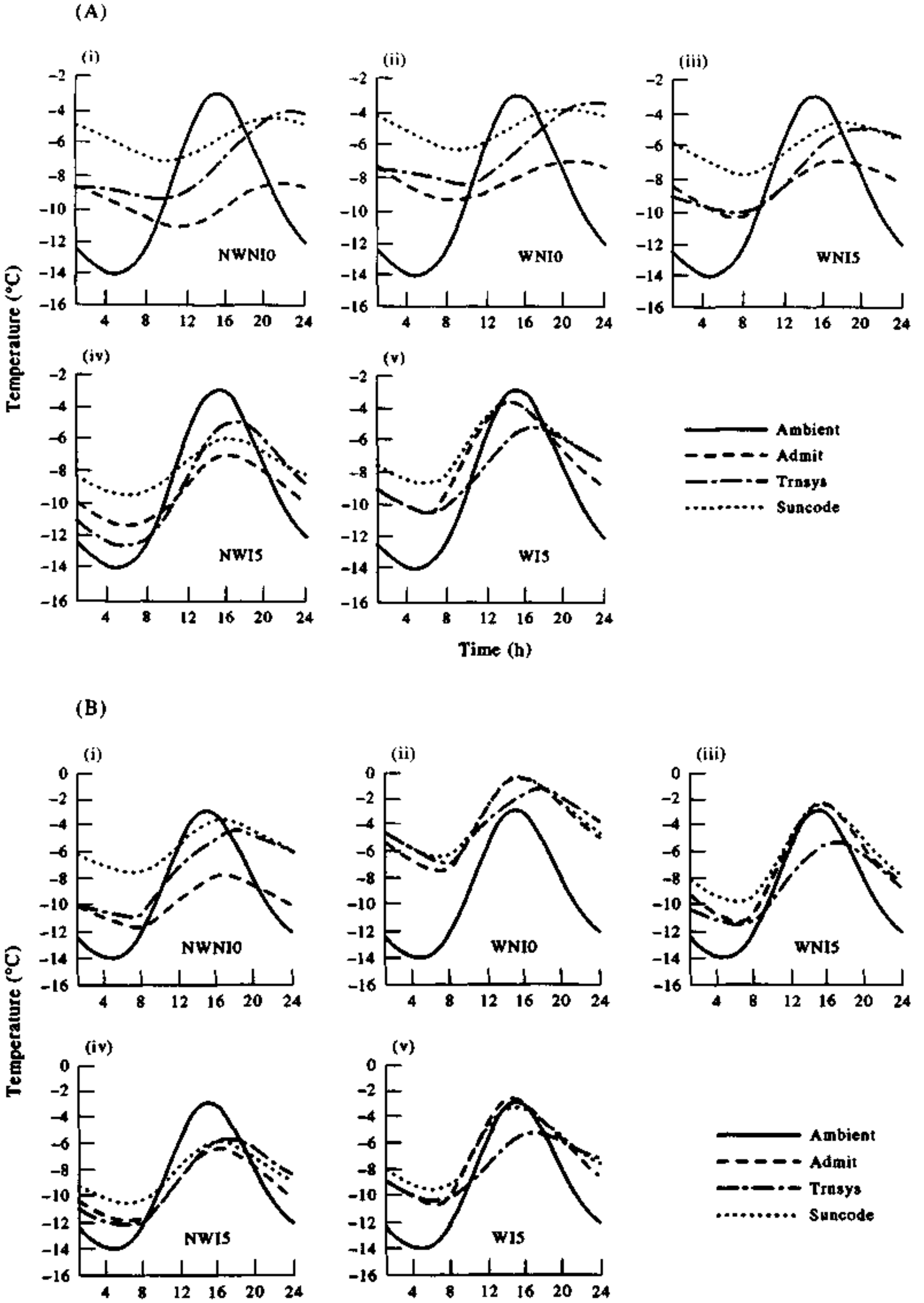


Fig. 7. Hourly variation of room temperature for Leh in January for (a) heavy construction (room size 4 × 4 × 3 m), (b) light construction (room size 4 × 4 × 3 m).

NOMENCLATURE

ach	number of air changes per hour
A	area of fabric (m^2)
c	specific heat of the building material (J/kg K)
$C_{\inf}$	infiltration coefficient
C_v	ventilation coefficient
h	convective heat transfer coefficient (W/m^2 K)
I	radiation flux (W/m^2)
k	thermal conductivity of the building material (W/m K)
L	thickness of the elements (walls/roof) (m)
M_r	thermal mass of the room air (J/K)

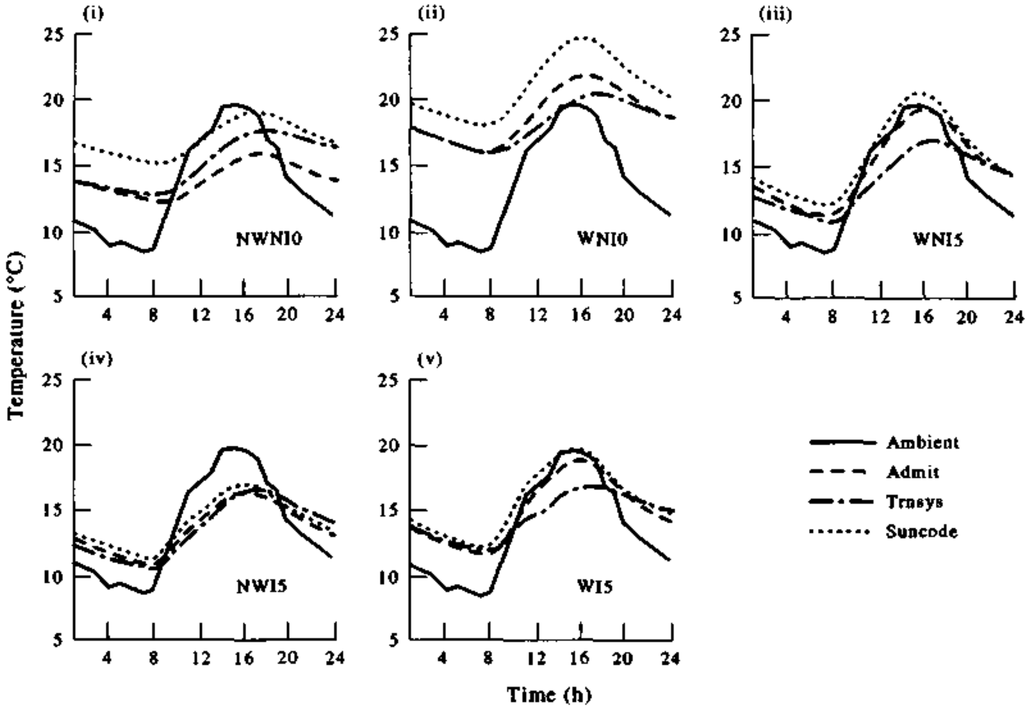


Fig. 8. Variation of room temperature for Delhi in January for light construction (room size 6 × 4 × 3 m).

P_n, Q_n, R_n, S_n	given by eqn (9)
q	rate of heat flow across any surface (W/m^2)
Q	heat flow across any fabric surface (W)
R	surface film resistance (m^2 K/W)
T	temperature (°C)
T_p	time period (s)
t	time (s)
V	volume of room (m^3)
X	coefficient matrix of order 13 × 13
Y	column matrix of order 13 × 1

Greek letters

α	absorptivity
ω	angular frequency (per hour)
ρ	density of the building material (kg/m^3)

Subscripts

d	door
f	floor
i	inside surface
n	nth harmonic
o	outside
R	room
R$_2$	adjacent room
v	ventilation
WL	wall
WN	window

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