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Applied Thermal Engineering 28 (2008) 1127–1137

APPLIED THERMAL ENGINEERING

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Development of CLTD values for buildings located in Kolkata, India

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Received 13 December 2006; accepted 20 August 2007
Available online 24 August 2007

Abstract

A one-dimensional, transient heat transfer model has been developed to estimate the cooling load temperature difference (CLTD) for buildings. Finite difference method has been used to solve the governing partial differential equation with suitable initial and boundary conditions. A recently developed ambient temperature model for predicting local dry bulb temperatures and a sky radiation model that considers the effect of local relative humidity has been used to generate CLTD values for different types of roofs and walls. Comparisons have been made between the computed and ASHRAE CLTD values. At standard conditions specified in ASHRAE handbooks, a reasonably good agreement was found between computed and ASHRAE CLTD values for roofs and walls. However, there is marginal to considerable differences between the computed and ASHRAE CLTD values, when the calculations are carried out for Kolkata, India.
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Keywords: Building walls; Roofs; Cooling load; CLTD; Weather data; ASHRAE

1. Introduction

Selection of a suitable air conditioning system for a building requires accurate information regarding the cooling load on the building. Based on the cooling load, vital decisions regarding the required capacity of the air conditioning system, volumetric flow rates of air and the duct dimensions, building energy consumption due to air conditioning system, etc. are made. In many buildings the heat gain through the external opaque walls and roof (fabric heat gain) constitutes a major portion of the total cooling load. Accurate estimation of cooling load due to fabric heat gain is quite complicated and time consuming as it is highly transient in nature due to thermal storage effects of the building mass and ever changing external conditions. In addition, the dependence of fabric heat gain on the location, shape and orientation of the building, as well as the internal radiative heat transfer interactions between different surfaces of the conditioned space, further complicate the problem.

Over the years, several methods have been developed to estimate the building cooling load due to fabric heat gain. The exact method involves the application of heat balance equation to the inner surfaces and finding a solution to the transient heat conduction equation for the walls and roof using suitable numerical methods such as finite difference method. The exact method is rigorous requiring the use of computers, but it is also direct and can be used easily for parametric studies. An alternate method is the use of conduction transfer functions. The transfer function method is less rigorous in terms of computation and is quite user-friendly. However, the transfer functions are available only for certain representative walls and roofs, and for others, these have to be obtained either from experiments or by using the heat balance method.

Based on the concept of transfer functions, three methods, namely, transfer function method (TFM), cooling load temperature difference (CLTD)/solar cooling load (SCL)/cooling load factor (CLF) method and total equivalent temperature difference (TETD)/time averaging (TA) method have been developed over the years for estimating cooling loads on buildings. The transfer function method (TFM) is a two-step procedure. For instance, the cooling

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doi:10.1016/j.applthermaleng.2007.08.005

Nomenclature

A	area of the surface (wall/roof) (m^2)
CLTD	cooling load temperature difference (°C)
G	rate at which solar radiation is incident per unit area (W/m^2)
I_t	total radiation falling on a unit surface in an hour (kJ/m^2 h)
L	total thickness of wall (m)
ΔL	difference between the meridian used in calculating standard time and the local meridian (s)
L_i	thickness of the ith layer (m)
RH	relative humidity
T_a	ambient temperature (°C)
T_{dp}	dew point temperature (°C)
T_i	initial temperature of the wall or roof (°C)
T_{max}	maximum ambient temperature in a day (°C)
T_{min}	minimum ambient temperature in a day (°C)
T_r	indoor temperature (K)
T_{sky}	sky temperature (K)
U	overall heat transfer coefficient of the structure (wall/roof) (W/m^2 K)
C_p	specific heat capacity of the material in concern (J/kg K)
h_1	heat transfer coefficient at the outside surface of the wall (W/m^2 K)
h_2	surface heat conductance at the inside surface of the wall (W/m^2 K)
k	thermal conductivity (W/m K)
k_i	thermal conductivity of the ith layer (W/m K)
n	total number of layers
r_c	roof check coefficient ($r_c = 0$ for wall and $r_c = 1$ for roof)
t	solar time (h)
t_{max}	hour of occurrence of T_{max} (h)
t_{min}	hour of occurrence of T_{min} (h)

Greek symbols

α	thermal diffusivity (m^2/s)
α_s	outside wall surface absorptivity
ε	emissivity of the surface
ε_s	outside wall surface emissivity
θ_m^p	normalized temperature at the mth grid point, at pth time step
ρ	density (kg/m^3)
σ	Stefan–Boltzman constant ($\sigma = 5.6697 \times 10^{-8}$ W/m^2 K^4)

load due to heat gain through the walls and roof is calculated in two steps. In the first step, the fabric heat gain is calculated using the conduction transfer function coefficients and in the second step, room transfer function coefficients are used to convert the heat gain into cooling load. Thus the accuracy of cooling load calculations using TFM depends very much on the accuracy of transfer function coefficients. Due to its user-friendliness, TFM is a widely used computer-aided load calculation method in air conditioning industry [1]. Unlike the TFM method, the cooling load temperature difference (CLTD)/solar cooling load (SCL)/cooling load factor (CLF) method is a one-step method. In this method, the cooling load temperature difference (CLTD) is used for calculating the cooling load due to fabric heat gain by multiplying it with the UA-value of the building element (where U is the overall heat transfer coefficient of the building wall or roof and A is its surface area). Hourly values of CLTD for representative walls and roofs are available in the form of tables. These CLTD values are normally generated using the TFM method for the particular walls and roofs. Thus the CLTD/SCL/CLF method is much simpler than the TFM method and is also very widely used for manual calculation and estimation of building cooling loads. However, the accuracy of this method once again depends on the transfer function coefficients, if TFM is used for generating the CLTD values. It is also possible to generate the CLTD values for representative walls and roof using the heat balance method, and by solving the fundamental transient heat conduction equation with appropriate initial and boundary conditions using a suitable numerical method. As mentioned before, though this method requires the use of computers for generating the CLTD values, it can be used very well for all kinds of walls and roofs including those not covered under TFM.

Using transfer functions, ASHRAE has developed CLTD values for exterior walls and roofs based on solar radiation typical of 40°N for July 21, for typical walls and roofs used in North America with certain inside and outside conditions [2]. The ASHRAE CLTD tables are widely used for estimating the cooling loads on air conditioned buildings. Even though ASHRAE has suggested correction factors for conditions other than those used in the computation of standard CLTD values, the accuracy of the CLTD values thus computed is questionable for locations other than 40°N, especially below 24°N as stated by Chaiyapinunt et al. [3]. This paper presents the development of CLTD values using the fundamental heat balance equation and solving the transient heat conduction equation using the conventional finite difference method, for typical building walls and roofs located in Kolkata (22.65°N, 88.45°E), India. The CLTD values are generated using a more recent ambient temperature model and other relevant local weather conditions. The generated CLTD values are compared with the CLTD values presented by ASHRAE.

2. Problem formulation

A multilayered roof and a similar wall of total thickness L is considered as shown in Fig. 1. Each layer is homogenous in itself with constant thermal properties. The dimensions of the wall in Y and Z directions are assumed to be very large; hence heat transfer has been considered to be one-dimensional across the cross section of the wall. To simplify the problem, the thermal capacity of the furniture in the conditioned space is assumed to be negligible, thus neglecting the dynamic heat storage effect of the furniture and the consequent variation in room temperature. Thus the conditioned space temperature T_r is assumed to be constant. The outside surface of the wall/roof is exposed to the atmosphere, and therefore experiences heat transfer, mainly by solar radiation and convection. Heat exchange at the outside roof surface also takes place by sky radiation. The solar radiation G, the atmospheric temperature T_a and the sky temperature T_{sky}, all vary with location, time of the day, day of the month and month of the year. As a result, heat transfer across the wall is transient and site specific. At the inside surface heat transfer takes place by convection and radiation. However, to simplify the problem, a surface heat conductance, h_2, that combines the effects of convection and radiation is used for the inner surface.

The transient, one-dimensional heat transfer through a layer (of a wall/roof) of constant homogeneous thermal properties is represented by the equation

$$\frac{\partial^2 T}{\partial x^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{1}$$

where

$$\alpha = k/\rho C_p \tag{2}$$

Eq. (1) is subject to the initial condition

$$T(x,0) = T_i \tag{3}$$

and boundary conditions

$$-k\frac{\partial T(0,t)}{\partial x} = h_1(T_a - T(0,t)) - \varepsilon_s \sigma r_c\left((T(0,t))^4 - T_{sky}^4\right) + \alpha_s G \tag{4}$$

$$-k\frac{\partial T(L,t)}{\partial x} = h_2(T(L,t) - T_r) \tag{5}$$

The governing equation, the initial condition and the boundary conditions are normalized using non-dimensional parameters given in Table 1.

The normalized governing equations are given below:

$$\frac{\partial^2 \theta}{\partial X^2} = \frac{\partial \theta}{\partial \tau} \tag{6}$$

Initial condition

$$\theta(X,0) = 1, \quad \text{for } 0 \leqslant X \leqslant 1 \tag{7}$$

Table 1
Definition of dimensionless parameters

Parameter	Definition	Name
X	$X = \frac{x}{L}$	Normalized length
τ	$\tau = \frac{\alpha t}{L^2}$	Fourier number (*Fo*)
θ	$\theta(X,\tau) = \frac{T(x,t)-T_r}{T_i-T_r}$	Normalized temperature
θ_a	$\theta_a(\tau) = \frac{T_a(t)-T_r}{T_i-T_r}$	Normalized atmospheric temperature
θ_{sky}	$\theta_{sky}(\tau) = \frac{T_{sky}(t)-T_r}{T_i-T_r}$	Normalized sky temperature
Bi_1	$Bi_1 = \frac{h_1 L}{k_1}$	Biot number (at the outside wall surface)
Bi_2	$Bi_2 = \frac{h_2 L}{k_n}$	Biot number (at the inside wall surface)
U_{sky}	$U_{sky} = r_c \frac{L}{k_1}\frac{\varepsilon_s \sigma}{24}\sum_{t=1}^{24}\frac{(T(0,t))^4-(T_{sky}(t))^4}{T(0,t)-T_{sky}(t)}$	Sky radiation coefficient
R	$R = \alpha_s \frac{L/k}{T_i-T_r} G$	Normalized solar radiation
s	$s = \frac{\Delta\tau}{\Delta X^2}$	Mesh ratio parameter
s_i	$s_i = \frac{2k_i}{\rho_i C_{p_i}+\rho_j C_{p_j}}\frac{\Delta t}{\Delta x^2},\ j = i+1$	
s_j	$s_j = \frac{2k_j}{\rho_i C_{p_i}+\rho_j C_{p_j}}\frac{\Delta t}{\Delta x^2},\ j = i+1$	
s_{ij}	$s_{ij} = \frac{2(k_i+k_j)}{\rho_i C_{p_i}+\rho_j C_{p_j}}\frac{\Delta t}{\Delta x^2},\ j = i+1$	

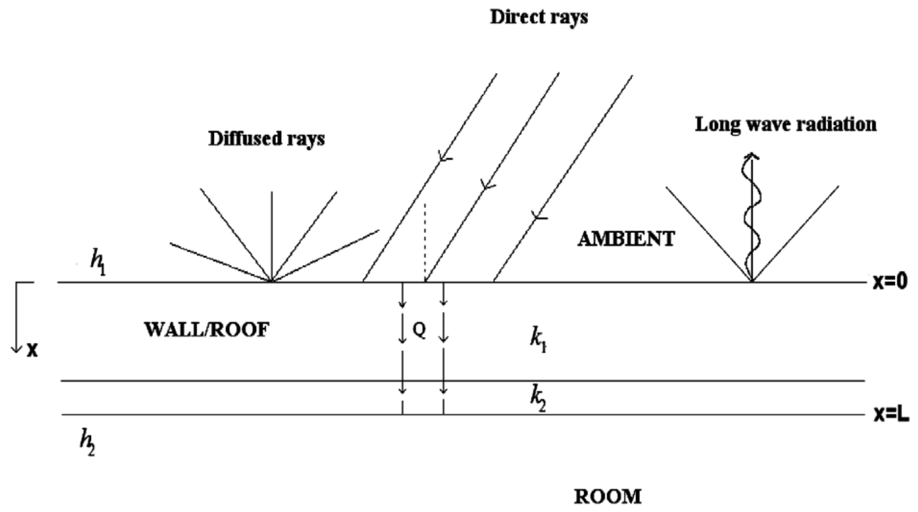

Fig. 1. External wall or roof of a building envelop.

Outside wall surface boundary condition

$$-\frac{\partial\theta}{\partial X}(0,\tau) = Bi_1(\theta_{\mathrm{a}}(\tau) - \theta(0,\tau)) + U_{\mathrm{sky}}(\theta_{\mathrm{sky}}(\tau) - \theta(0,\tau)) + R \tag{8}$$

Inside wall surface boundary condition

$$-\frac{\partial\theta}{\partial X}(1,\tau) = Bi_2(\theta(1,\tau)) \tag{9}$$

3. Method of solution

The governing equation, Eq. (6), is a parabolic partial differential equation, with an initial boundary condition, Eq. (7), and two first order differential boundary conditions, Eqs. (8) and (9). The set of governing equations is solved by employing finite difference method (FDM). A fully implicit scheme, with a forward difference approximation on the time derivative is used for discretization.

General finite difference equation

$$\theta_m^p = -s\left(\theta_{m+1}^{p+1} + \theta_{m-1}^{p+1}\right) + (1+2s)\left(\theta_m^{p+1}\right) \tag{10}$$

The finite difference equations for the boundary conditions are derived by applying the general finite difference equation, with central difference approximation, on the non-dimensionalized boundary conditions, i.e., Eqs. (8) and (9).

Finite difference equation for the outside wall surface boundary condition

$$\theta_0^p = -2s\left(\theta_1^{p+1}\right) + (1+2s+2\Delta Xs(Bi_1+U_{\mathrm{sky}}))\left(\theta_0^{p+1}\right) - 2\Delta Xs\left(Bi_1\left(\theta a^{p+1}\right) + U_{\mathrm{sky}}\left(\theta_{\mathrm{sky}}^{p+1}\right) + R\right) \tag{11}$$

Finite difference equation for the inside wall surface boundary condition

$$\theta_m^p = -2s\left(\theta_{m-1}^{p+1}\right) + (1+2s+2\Delta Xs(Bi_1))\left(\theta_m^{p+1}\right) \tag{12}$$

The total number of grid points is $m+1$, i.e. from 0 to m.

The grid spacing has been fixed in such a way that there is a grid point located at each interface between the different layers of the wall. The thermal properties are different on either side of the interface grid point. Hence the general finite difference equation cannot be applied to derive the equation at the interface grid points. Instead energy balance is applied at the interface grid point; and consequently the finite difference equation is derived with central difference approximation.

Finite difference equation at the interfaces

$$\theta_m^p = -2s_1\left(\theta_{m-1}^{p-1}\right) - 2s_2\left(\theta_{m+1}^{p+1}\right) + (1+2s_{12})\left(\theta_m^{p+1}\right) \tag{13}$$

The above system of finite difference equations i.e., Eqs. (10)–(13), is solved by the matrix inversion method.

Estimation of cooling load temperature difference (CLTD)

The cooling load (Q) on a building through a wall or roof is given by

$$Q = UA(\mathrm{CLTD}) \tag{14}$$

where the overall heat transfer coefficient is given by

$$U = \left(\frac{1}{h_1} + \sum_{i=1}^{n}\frac{L_i}{k_i} + \frac{1}{h_2}\right)^{-1} \tag{15}$$

The cooling load can also be obtained from the equation

$$Q = h_2A(T(L,t) - T_{\mathrm{r}}) \tag{16}$$

Thus Q can be calculated from the temperature profile generated using the finite difference method as discussed before. Consequently the CLTD can be calculated using Eqs. (14) and (16) as

$$CLTD = \frac{h_2}{U}(T(L,t) - T_{\mathrm{r}}) \tag{17}$$

The above calculations, i.e. solving the 1-D, transient heat transfer equation applying finite difference method; generating the temperature profile for a wall/roof; and estimating the CLTD as well as plotting the same for a particular structure (wall/roof) is done using MATLAB.

4. Ambient temperature model

Various models are available to estimate the ambient temperature at a given location. The monthly averaged temperature model proposed by Satyamurty and Babu [4] is used here. It predicts the hourly ambient temperature of a day in terms of the maximum and minimum temperatures of that day (i.e. $T_{\max}$ and $T_{\min}$), and their respective hours of occurrence.

The ambient temperature at time t (local standard time, taken in hours) is given by

$$T_a(t) = A - B\cos(2\pi\bar{t}^D) - F \tag{18}$$

where

$$\bar{t} = \begin{cases} (t+24-t_{\min})/24 & \text{if } (t < t_{\min}) \\ (t-t_{\min})/24 & \text{if } (t \geqslant t_{\min}) \end{cases} \tag{19}$$

$$\begin{aligned} A &= 0.5\times(T_{\max}+T_{\min}) \\ B &= 0.5\times(T_{\max}-T_{\min}) \end{aligned} \tag{20}$$

$$D = \frac{\ln(2)}{\ln(24/(t_{\max}-t_{\min}))} \tag{21}$$

$$F = \begin{cases} 0.22 & \text{if } (t < 18) \\ 1.25 & \text{if } (t \geqslant 18) \end{cases} \tag{22}$$

5. Solar radiation model

The model given in Sukhatme [5] for the prediction of hourly global radiation under clear sky conditions has been used here. This model, which was originally developed by ASHRAE is based on an exponential decay model, in which the beam radiation decreases with increased distance traversed through the atmosphere. This model uses three constants (A, B and C) for calculation of hourly beam and diffuse radiation. These constants depend on the day of the year and earth–sun distance. The values of these constants for the 21st day of each month obtained for US conditions, were initially reported by Threlkeld and Jordan [6], and later revised by Iqbal [7]. As shown by Sukhatme [5], sample calculations carried out for Nagpur, India (21°06′N, 79°03′E) and comparison with the actually measured data show that the use of the values A, B and C obtained on the basis of US data predicts a higher value for beam radiation and a lower value for diffuse radiation, thus tending to balance each other to some extent. Thus in the absence of a very accurate local solar radiation data, use of the above model along with the tabulated values of A, B, C may be justified for other locations also.

6. Sky radiation model

The sky radiation model given by Chen et al. [8] for a pond surface has been used here. The total heat exchange between the outer surface of the roof and the surroundings by long wave radiation is given by

$$Q = \varepsilon\sigma\left(T^4(0,t) - T^4_{\text{sky}}\right) \tag{23}$$

According to Chen et al. [8]

$$\begin{aligned} T^4_{\text{sky}} = {} & (0.736 + 0.00571(T_{\text{dp}} + 273) \\ & + 0.3318 \times 10^{-5}(T_{\text{dp}} + 273)^2)(T_{\text{a}} + 273)^4 \end{aligned} \tag{24}$$

The dew point temperature T_{dp} is derived using the Magnus–Tetens formula [9] for vapour pressure and is given by,

$$T_{\text{dp}} = \frac{b \times \mu(T_{\text{a}}, \text{RH})}{a - \mu(T_{\text{a}}, \text{RH})} \tag{25}$$

where

μ is given by

$$\begin{aligned} \mu(T_{\text{a}}, RH) &= \frac{a \times T_{\text{a}}}{b + T_{\text{a}}} + \ln(\text{RH}) \\ a &= 17.27 \\ b &= 237.7\ ^\circ\text{C} \end{aligned} \tag{26}$$

For walls, sky radiation is considered to be zero as suggested in ASHRAE [2]. This is justified as long wave radiation from the ground and other terrestrial objects approximately compensates for the sky's low emittance.

7. Results and discussion

The model presented here, calculates the hourly cooling load temperature difference, at any place on earth, on any day of the year, given appropriate weather data (i.e. the maximum and minimum temperature, their time of occurrence in the day and the relative humidity) and proper wall/roof specifications. The simulation has been run (iterated) over a span of 5 days, with an initial homogenous temperature distribution assumption, in order to arrive at a stable temperature profile, with negligible residual changes. The CLTD generated and documented, is that of the fifth day and is independent of the initial assumption. Table 2 shows the details of the roofs and walls considered in the present study. The mass per unit area and U-value for these roofs and walls have been obtained from the ASHRAE data charts [2]. Similar to the ASHRAE data [2], the surfaces of the walls and roof are assumed to be dark with an emissivity of 0.9.

Table 2
Roof and wall specifications

Roof/ wall No.	Description of construction	Mass/area (kg/m^2)	U-value (W/m^2 °C)
Roof 1	100 mm l.w. concrete	88	1.209
Roof 2	150 mm l.w. concrete	117	0.897
Roof 3	200 mm l.w. concrete	151	0.715
Roof 4	100 mm h.w. concrete with 25 mm insulation	254	1.136
Roof 5	150 mm h.w. concrete with 25 mm insulation	366	1.090
Wall 1	100 mm face brick + 100 mm common brick + 20 mm plaster	440	2.36
Wall 2	100 mm face brick + 100 mm clay tile + 20 mm plaster	347	2.16
Wall 3	100 mm face brick + 100 mm l.w. concrete block + 20 mm plaster	303	1.81
Wall 4	25 mm Stucco finish + 200 mm h.w. concrete + 20 mm plaster	5.32	2.78

Solving the system of finite difference equations, one can obtain the temperature gradient along the wall at different times of the day. Such a temperature profile is shown in Fig. 2 for wall 2 (from Table 2), facing North (2N), South (2S), East (2E) and West (2W), respectively, at 24.00 h. Fig. 3 shows the same for a flat roof (roof 4 from Table 2) but at different times of the day.

The above figures have been generated using the following input data:

- Location: Kolkata, India (22.65°N, 88.45°E).
- Date: July 21.
- Indoor temperature: 25.5 °C.
- Outdoor maximum temperature: 30.5 °C [10].
- Time of maximum temperature: 13.00 h [10].
- Outdoor minimum temperature: 26.6 °C [10].
- Time of minimum temperature: 05.00 h [10].
- Outside surface resistance: 0.059 m^2 °C/W [2].
- Inside surface resistance: 0.121 m^2 °C/W [2].

8. Comparison between computed and ASHRAE CLTD values at standard conditions

ASHRAE has presented CLTD data for the following standard conditions [2]:

- Latitude: 40°N.
- Outdoor maximum temperature: 35.0 °C.
- Time of maximum temperature: 15.00 h.
- Outdoor minimum temperature: 23.4 °C.
- Time of minimum temperature: 5.00 h.
- Range of temperature: 11.6 °C.

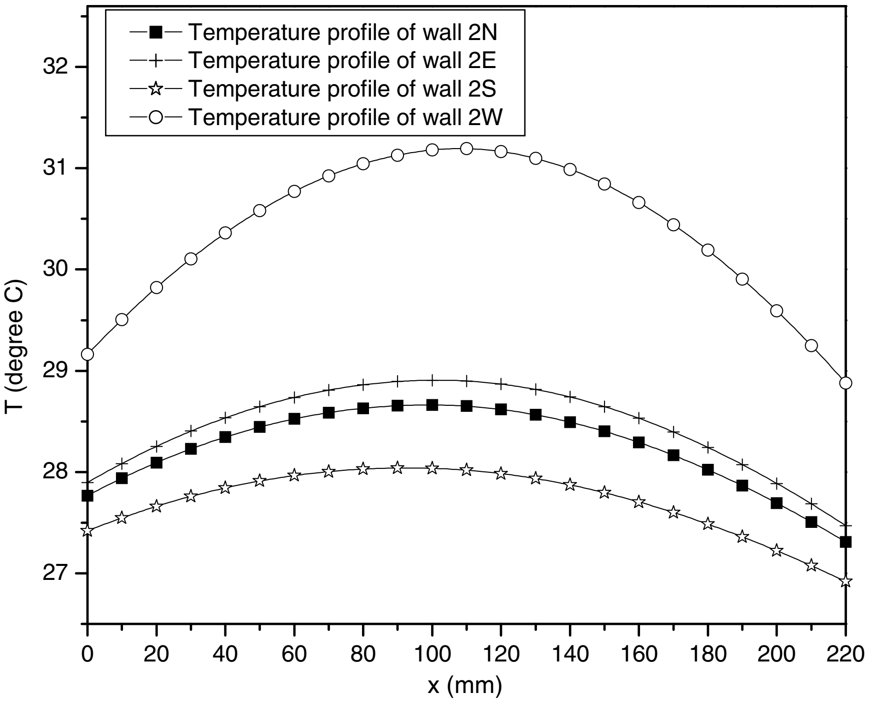

Fig. 2. Temperature profile of different orientations of wall 2 at 24.00 h.

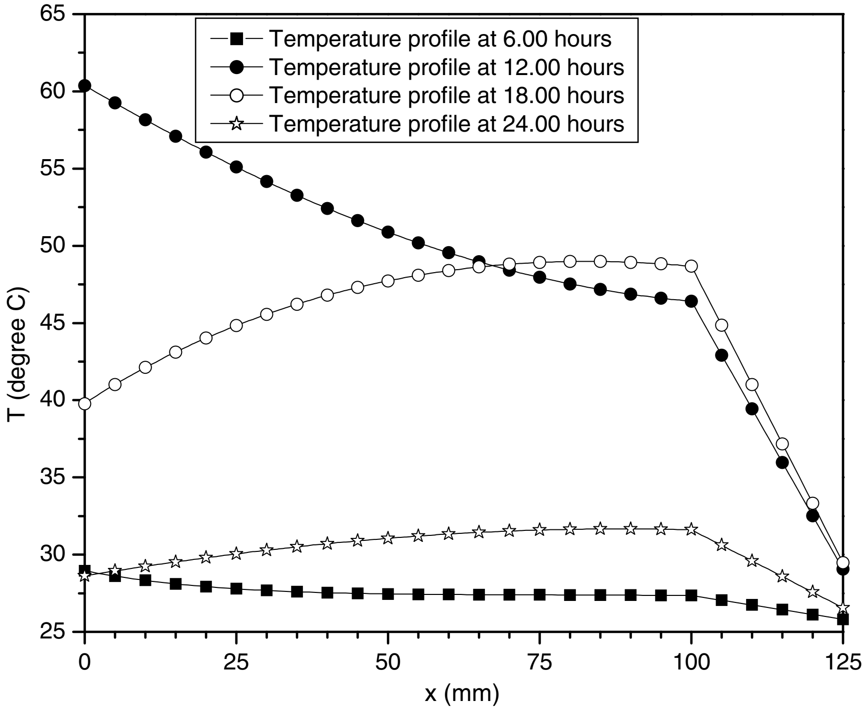

Fig. 3. Temperature profile of roof 4 at different times of the day.

For the above standard conditions, Fig. 4 shows a comparison between CLTD data calculated using the model presented in this paper and the ASHRAE data. Due to some ambiguity regarding the location of insulation for multi-layered roofs, results are obtained for both insulation inside (towards the conditioned space) and insulation outside (towards the outdoors). As shown, in case of the single layer roof (roof 1) the CLTD results agree fairly well with that given by ASHRAE [2], though there is a phase difference of about an hour. In case of the multi-layered roof (roof 4) agreement between ASHRAE values and computed values is good when the insulation is on the outside. The agreement between ASHRAE and the model data is reasonably good for wall 1S also as shown in the figure,

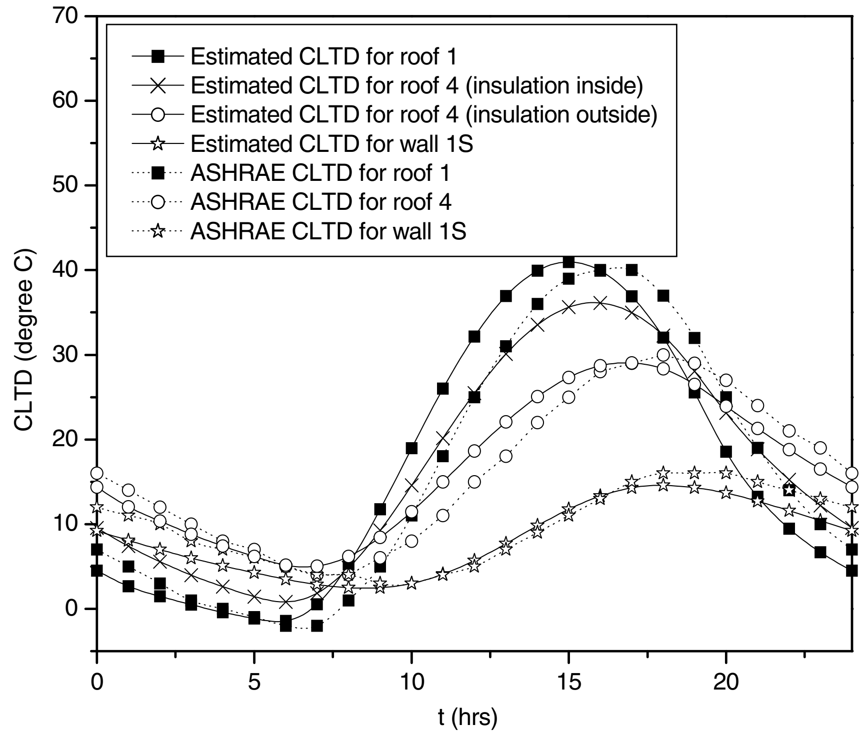

Fig. 4. Comparison between estimated CLTD and ASHRAE CLTD at 40°N.

Table 3
CLTD for different roofs at Kolkata on July 21st

Hr	Roof 1	Roof 2	Roof 3	Roof 4 (insulation outside)	Roof 4 (insulation inside)	Roof 5 (insulation outside)	Roof 5 (insulation inside)
1	2.4	8.0	14.6	10.6	6.2	15.439	13.7
2	2.0	6.4	12.5	9.3	5.0	14.289	12.2
3	1.7	5.1	10.7	8.1	4.1	13.23	10.8
4	1.4	4.1	9.2	7.0	3.4	12.246	9.6
5	1.1	3.4	7.8	6.1	2.8	11.327	8.6
6	1.0	2.7	6.7	5.3	2.3	10.472	7.6
7	2.0	2.3	5.8	5.2	2.9	9.7256	6.9
8	5.9	2.9	5.1	6.4	5.6	9.3537	6.8
9	12.2	5.2	5.1	8.8	9.9	9.5954	7.6
10	19.3	9.0	6.2	12.1	15.2	10.49	9.5
11	26.4	13.9	8.4	15.8	20.7	11.948	12.1
12	32.4	19.2	11.4	19.6	25.8	13.814	15.1
13	36.9	24.3	15.0	23.1	30.2	15.901	18.3
14	39.5	28.7	18.7	26.0	33.2	18.011	21.3
15	39.9	32.0	22.3	28.0	34.7	19.948	23.9
16	38.2	33.9	25.3	28.9	34.5	21.533	25.8
17	34.2	34.2	27.6	28.6	32.5	22.612	26.8
18	28.4	32.7	28.7	27.1	28.9	23.06	26.8
19	21.0	29.5	28.7	24.4	23.9	22.797	25.7
20	14.2	24.9	27.4	21.4	19.0	21.886	23.7
21	9.6	20.2	25.1	18.6	15.1	20.639	21.5
22	6.6	16.1	22.3	16.2	12.1	19.293	19.2
23	4.6	12.8	19.5	14.1	9.6	17.951	17.2
24	3.3	10.1	16.9	12.2	7.6	16.653	15.3
Max. CLTD (estimated)	39.9	34.2	28.7	28.9	34.7	23.06	26.8
Max. CLTD (ASHRAE)	39	35	29	29	29	24	24

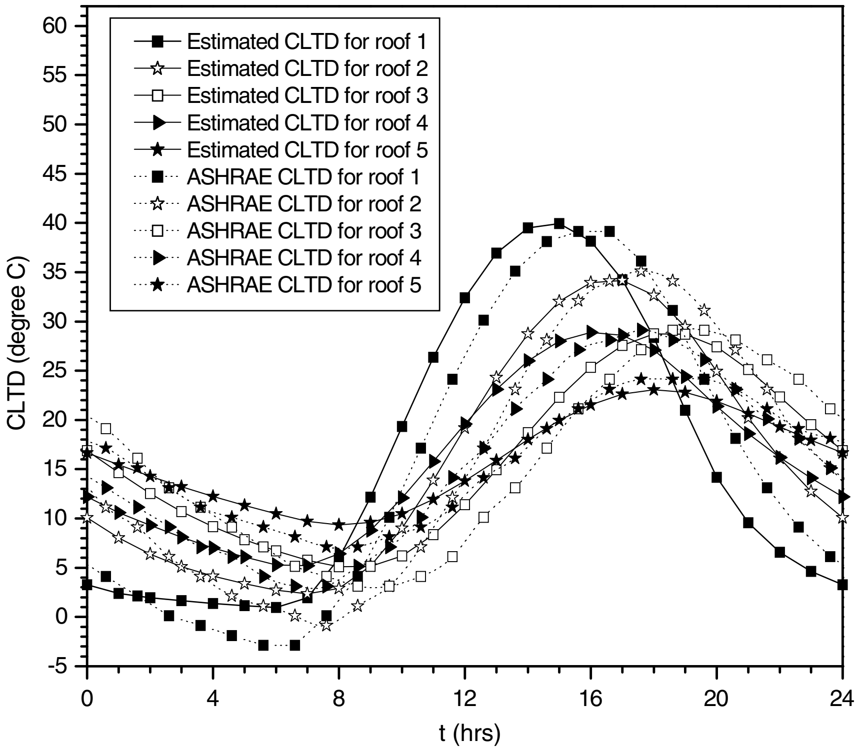

Fig. 5. Comparison between estimated CLTD and ASHRAE CLTD for different roofs at Kolkata.

Table 4
CLTD for different walls at Kolkata on July 21st

Hr	1N	1E	1S	1W	2N	2E	2S	2W	3N	3E	3S	3W	4N	4E	4S	4W
1	6.1	6.9	4.7	11.0	6.1	6.5	4.7	11.1	6.4	6.6	4.9	12.0	3.7	3.9	2.8	6.8
2	5.4	6.1	4.3	9.7	5.3	5.7	4.2	9.5	5.5	5.7	4.3	10.1	3.2	3.4	2.5	5.9
3	4.9	5.5	3.9	8.6	4.7	5.0	3.7	8.2	4.7	4.9	3.7	8.6	2.8	3.0	2.2	5.0
4	4.4	4.9	3.5	7.6	4.1	4.4	3.3	7.1	4.1	4.2	3.3	7.3	2.4	2.6	1.9	4.3
5	3.9	4.4	3.2	6.7	3.6	3.9	3.0	6.2	3.6	3.7	2.9	6.2	2.1	2.3	1.7	3.7
6	3.5	3.9	2.8	5.9	3.2	3.4	2.6	5.3	3.1	3.2	2.6	5.3	1.9	2.0	1.5	3.2
7	3.2	3.6	2.6	5.2	2.9	3.2	2.4	4.6	2.9	3.2	2.3	4.6	1.7	1.9	1.4	2.8
8	3.2	4.2	2.4	4.7	3.2	4.4	2.3	4.2	3.5	5.3	2.4	4.3	2.0	2.8	1.4	2.6
9	3.7	6.0	2.5	4.5	4.0	7.3	2.5	4.1	4.8	9.5	2.9	4.5	2.6	4.8	1.6	2.6
10	4.4	8.6	2.8	4.5	5.0	10.8	3.0	4.4	6.3	14.4	3.8	5.0	3.3	7.2	2.0	2.8
11	5.1	11.2	3.3	4.7	5.8	14.1	3.7	4.8	7.6	18.6	4.9	5.9	3.9	9.3	2.5	3.2
12	5.7	13.3	3.9	5.1	6.6	16.4	4.5	5.4	8.6	21.4	6.1	6.9	4.4	10.9	3.1	3.7
13	6.2	14.5	4.6	5.6	7.2	17.5	5.5	6.1	9.4	22.5	7.4	7.9	4.9	11.5	3.8	4.2
14	6.7	14.9	5.4	6.3	7.8	17.5	6.4	7.2	10.2	22.1	8.7	9.4	5.3	11.5	4.4	4.9
15	7.1	14.7	6.1	7.5	8.3	16.9	7.3	8.9	10.8	21.0	9.7	11.9	5.6	11.1	5.0	6.1
16	7.6	14.3	6.7	9.4	8.8	16.1	7.9	11.5	11.3	19.8	10.4	15.3	5.9	10.5	5.4	7.8
17	8.1	13.8	7.1	11.8	9.4	15.3	8.4	14.7	12.0	18.6	10.7	19.4	6.2	10.0	5.6	9.8
18	8.6	13.2	7.4	14.4	10.0	14.4	8.5	17.9	12.6	17.2	10.8	23.3	6.6	9.3	5.6	11.8
19	9.1	12.5	7.4	16.5	10.5	13.4	8.5	20.1	13.0	15.8	10.4	25.7	6.8	8.6	5.5	13.1
20	9.1	11.6	7.2	17.2	10.4	12.2	8.1	20.3	12.5	14.1	9.7	25.1	6.7	7.8	5.2	13.1
21	8.8	10.6	6.8	16.6	9.6	10.9	7.4	18.9	11.3	12.3	8.6	22.7	6.1	6.9	4.7	12.0
22	8.1	9.6	6.3	15.3	8.7	9.7	6.7	16.8	10.0	10.6	7.6	19.7	5.5	6.0	4.2	10.6
23	7.4	8.6	5.8	13.8	7.8	8.5	6.0	14.7	8.6	9.1	6.6	16.8	4.8	5.3	3.7	9.2
24	6.7	7.7	5.3	12.3	6.8	7.4	5.4	12.8	7.4	7.8	5.7	14.2	4.2	4.6	3.2	7.9
Max. CLTD (estimated)	9.1	14.9	7.4	17.2	10.5	17.5	8.5	20.3	13.0	22.5	10.8	25.7	6.8	11.5	5.6	13.1
Max. CLTD (ASHRAE)	10	17	11	22	10	17	11	22	11	20	14	26	9	16	9	19

though there is again some phase difference. The small difference between the calculated and ASHRAE CLTD values can be attributed to the following factors.

- In case of walls, ASHRAE categorizes each wall into a particular type (A, B, C, or D), but gives single CLTD values for all these four types, without making any distinction between them, which as a result, may involve some averaging of CLTD values.

- The coefficients A, B and C, used to calculate the solar radiation heat gain (as given in the solar radiation model) are those given by Iqbal [7], and therefore are far more recent than the values given by Threlkeld and Jordan [6], which have been used by ASHRAE.

9. CLTD calculated for different walls and roofs in Kolkata

CLTD data has been generated for Kolkata, India (22.65°N, 88.45°E). This has been plotted along with the corresponding ASHRAE CLTD (for Kolkata). The ASHRAE CLTD values for Kolkata are obtained by adding or subtracting the difference in standard (on which ASHRAE

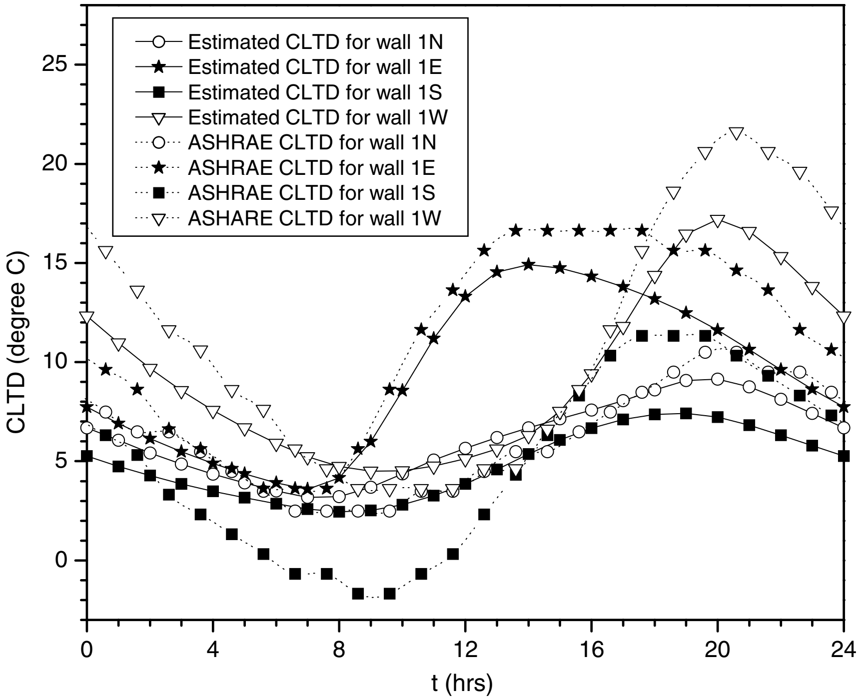

Fig. 6. Comparison between estimated CLTD and ASHRAE CLTD for different orientations of wall 1 at Kolkata.

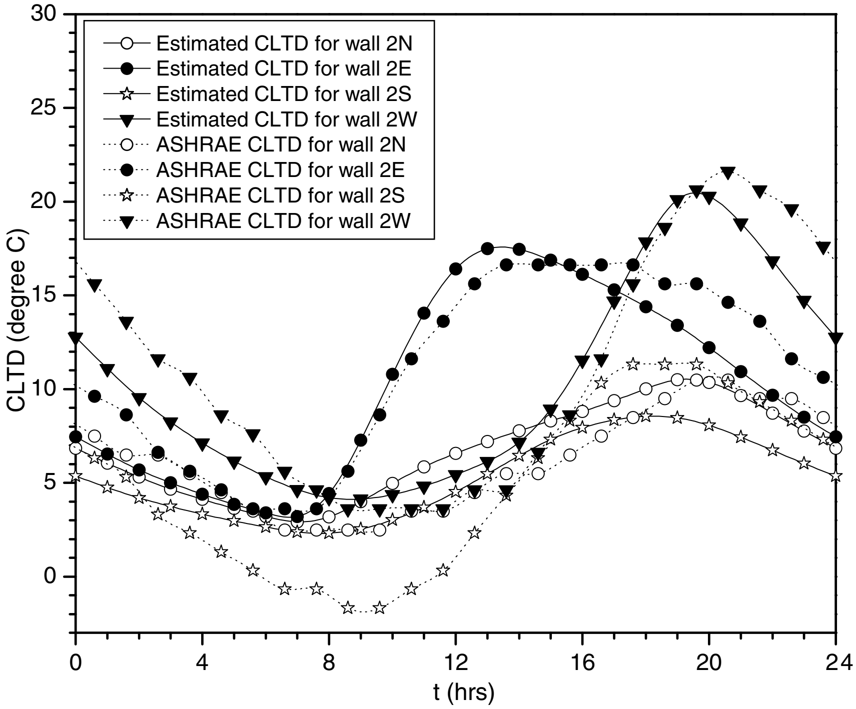

Fig. 7. Comparison between estimated CLTD and ASHRAE CLTD for different orientations of wall 2 at Kolkata.

tables are based) and actual average temperatures (for Kolkata) to or from the CLTD values obtained from ASHRAE tables. The weather data (i.e. the maximum and minimum temperature and relative humidity and their time of occurrence in the day) presented by Mani [10], has been used for the ambient temperature model and the sky radiation model. Other conditions for Kolkata are as stated before. The different walls and roofs considered here have been taken from the list given by ASHRAE [2]. This has been done in order to demonstrate the expected difference between the CLTD calculated and that given by ASHRAE.

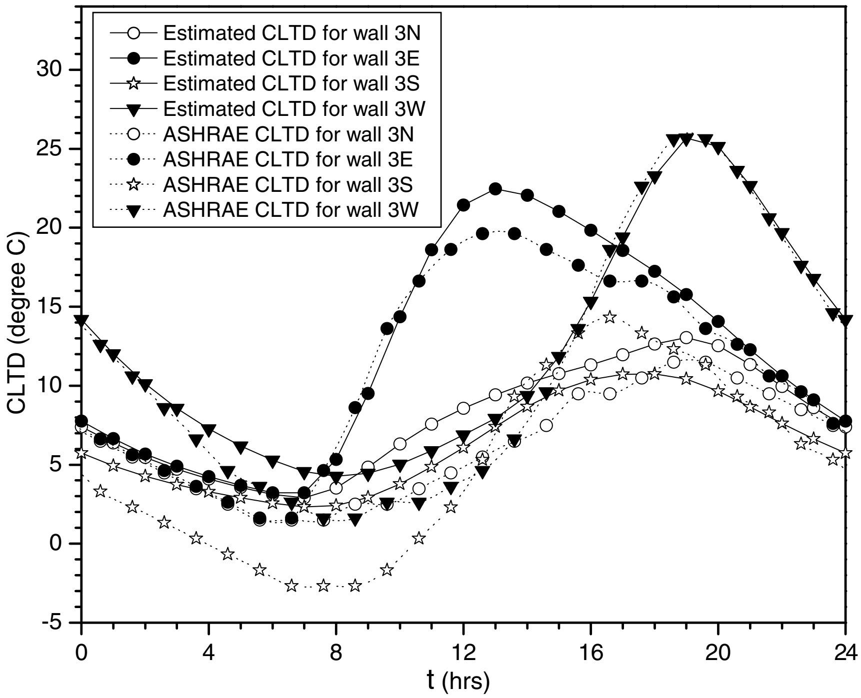

Fig. 8. Comparison between estimated CLTD and ASHRAE CLTD for different orientations of wall 3 at Kolkata.

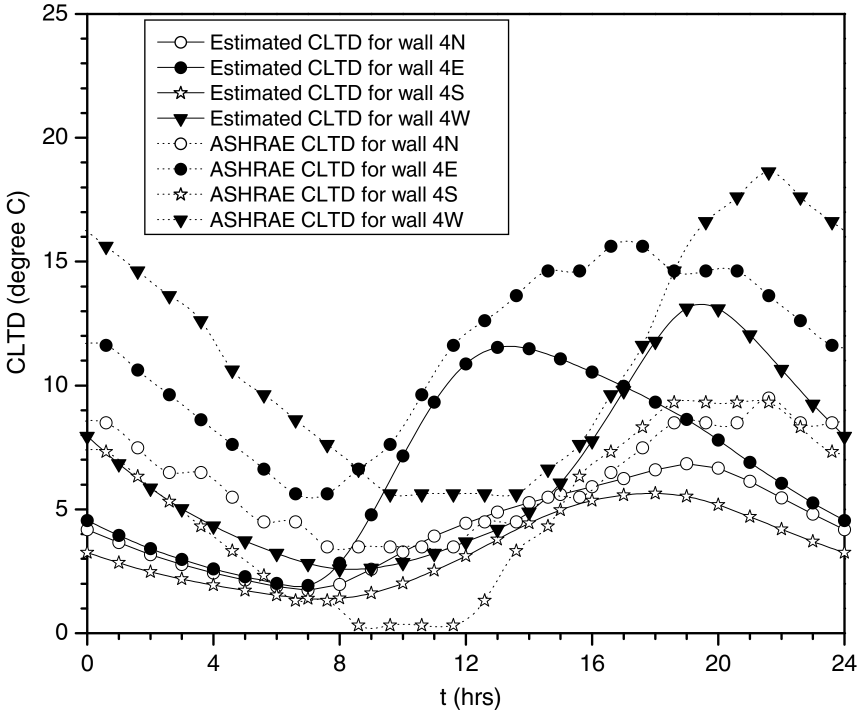

Fig. 9. Comparison between estimated CLTD and ASHRAE CLTD for different orientations of wall 4 at Kolkata.

Table 3 gives the CLTD calculated for five different roofs (roofs 1–5) at Kolkata. The comparison of the same with the corresponding ASHRAE CLTD is shown in Fig. 5 with insulation outside in case of multi-layered roofs. From Table 3 it is clear that the difference between maximum CLTD values calculated using the present model and the CLTD values obtained using ASHRAE data is less than 1 °C for single layered roofs, and is less than 1 °C for the multi-layered roofs also, when the insulation is assumed to be on the outside. However, there is some time lag between the ASHRAE and computed results.

Table 4 gives the CLTD calculated for four different walls (walls 1, 2, 3 and 4, respectively) for each of the four directions (i.e. N, S, E, W), at Kolkata. The comparison of the same with the corresponding ASHRAE CLTD is shown in Figs. 6–9, respectively. From Table 4 it is observed that the difference between maximum CLTD values calculated using the present model and the CLTD values obtained using ASHRAE data varies from 0.5 °C to about 6 °C, depending upon the type of the wall and its orientation. This shows that for non-standard conditions, the ASHRAE data is generally good for roofs, whereas the difference between actual CLTD values and ASHRAE data can be considerable in case of walls.

In all the figures and tables, 1N, 2S, etc. refer to the type of the wall, with the number denoting the wall number (according to Table 2), and the succeeding alphabet (N, S, E, W) denoting the orientation of the wall in North, South, East and West directions, respectively.

10. Conclusions

This paper describes the estimation of cooling load temperature difference (CLTD) values for building envelopes, using the finite difference method (FDM). A MATLAB program has been used to generate CLTD values for different walls and roofs, both at 40°N and for the city of Kolkata, India. The CLTD values calculated for 40°N (standard conditions) agree fairly well with that given by ASHRAE, proving the validity of model presented. CLTD values of different roofs for building located in Kolkata (non-standard conditions) are found to agree reasonably well with the values obtained from ASHRAE tables with corrections for latitude, range, etc. However, the difference between the computed and calculated values in case of walls can be small to considerable. The reasons for this may be attributed to the use of more recent and appropriate ambient temperature and solar radiation models for computing CLTD values and possibly grouping of the different walls into single category by ASHRAE. Thus it may be concluded that the CLTD values for different types of walls as given by ASHRAE are not so accurate for locations other than those for which it is computed, especially with local weather variations. The model presented here can be used to calculate the cooling load due to roofs and walls other than those listed in the ASHRAE tables also. In fact, if thermal specifications are available for building materials local to the concerned region, the cooling load calculation of buildings in that region can be done with greater accuracy. As mentioned before, the model used here does not consider the influence of thermal capacity of the objects inside the conditioned space and assumes constant room temperature. However, the model can be extended to consider these affects also, so that one can calculate the instantaneous heat transfer rates and the conditioned space temperature, if the detailed specifications of the objects inside the conditioned space are known.

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