CHAPTER 4

THERMAL PERFORMANCE OF BUILDINGS

Contents

4.1 INTRODUCTION

The thermal performance of a building refers to the process of modeling the energy transfer between a building and its surroundings. For a conditioned building, it estimates the heating and cooling load and hence, the sizing and selection of HVAC equipment can be correctly made. For a non-conditioned building, it calculates temperature variation inside the building over a specified time and helps one to estimate the duration of uncomfortable periods. These quantifications enable one to determine the effectiveness of the design of a building and help in evolving improved designs for realising energy efficient buildings with comfortable indoor conditions. The lack of proper quantification is one of the reasons why passive solar architecture is not popular among architects. Clients would like to know how much energy might be saved, or the temperature reduced to justify any additional expense or design change. Architects too need to know the relative performance of buildings to choose a suitable alternative. Thus, knowledge of the methods of estimating the performance of buildings is essential to the design of passive solar buildings.

In this chapter, we will discuss a simple method for estimating the thermal performance of a building and introduce a few simulation tools used for more accurate calculations.

Various heat exchange processes are possible between a building and the external environment. These are shown in Fig. 4.1. Heat flows by conduction through various building elements such as walls, roof, ceiling, floor, etc. Heat transfer also takes place from different surfaces by convection and radiation. Besides, solar radiation is transmitted through transparent windows and is absorbed by the internal surfaces of the building. There may be evaporation of water resulting in a cooling effect. Heat is also added to the space due to the presence of human occupants and the use of lights and equipments. The interaction between a human body and the indoor environment is shown in Fig. 4.2. Due to metabolic activities, the body continuously produces heat, part of which is used as work, while the rest is dissipated into the environment for maintaining body temperature. The body exchanges heat with its surroundings by convection, radiation, evaporation and conduction. If heat is lost, one feels cool. In case of heat gain from surroundings, one feels hot and begins to perspire. Movement of air affects the rate of perspiration, which in turn affects body comfort.

The thermal performance of a building depends on a large number of factors. They can be summarised as (i) design variables (geometrical dimensions of building elements such as walls, roof and

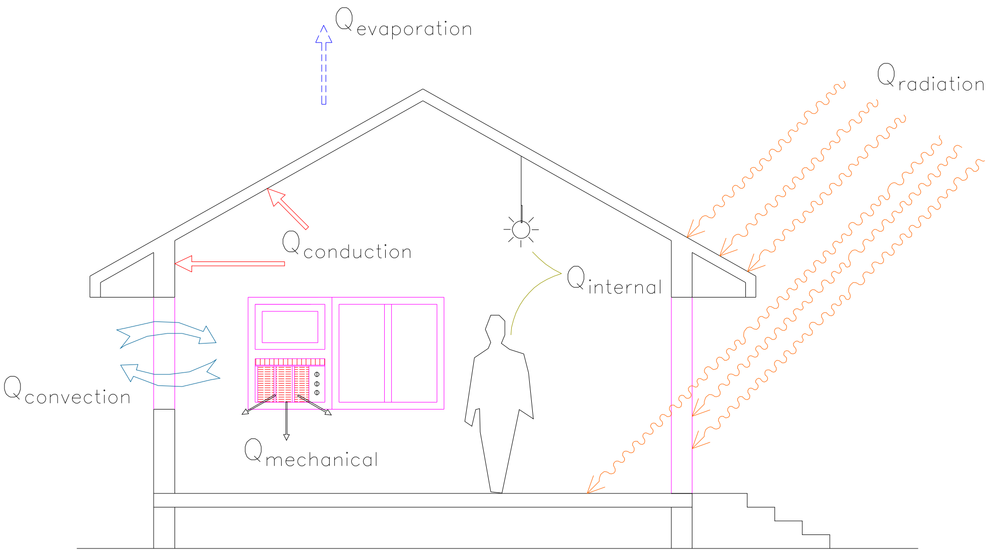

Fig. 4.1 Heat exchange processes between a building and the external environment

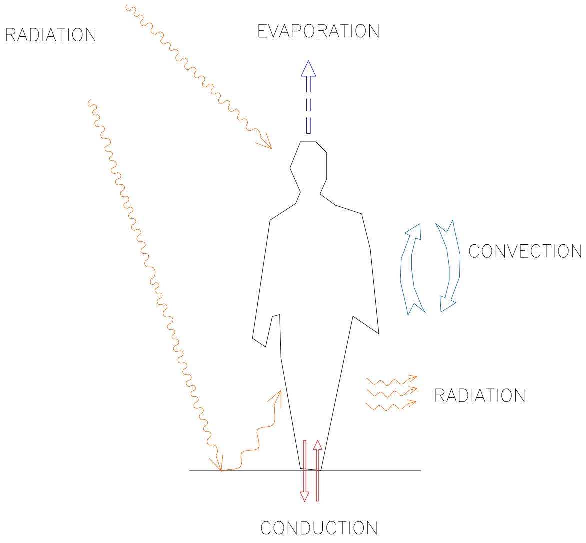

Fig. 4.2 Heat exchange processes between a human body and the indoor environment

windows, orientation, shading devices, etc.); (ii) material properties (density, specific heat, thermal conductivity, transmissivity, etc.); (iii) weather data (solar radiation, ambient temperature, wind speed, humidity, etc.); and (iv) a building's usage data (internal gains due to occupants, lighting and equipment, air exchanges, etc.). A block diagram showing various factors affecting the heat balance of a building is presented in Fig. 4.3. The influence of these factors on the performance of a building can be studied using appropriate analytical tools. Several techniques are available for estimating the performance of buildings. They can be classified under Steady State methods, Dynamic methods and Correlation methods. Some of the techniques are simple and provide information on the average load or temperature, on a monthly or annual basis. Others are complex and require more detailed input information. However, the latter perform a more accurate analysis and provide results on an hourly or daily basis. In this chapter, we discuss a simple method that is easy to understand and amenable to hand calculations.

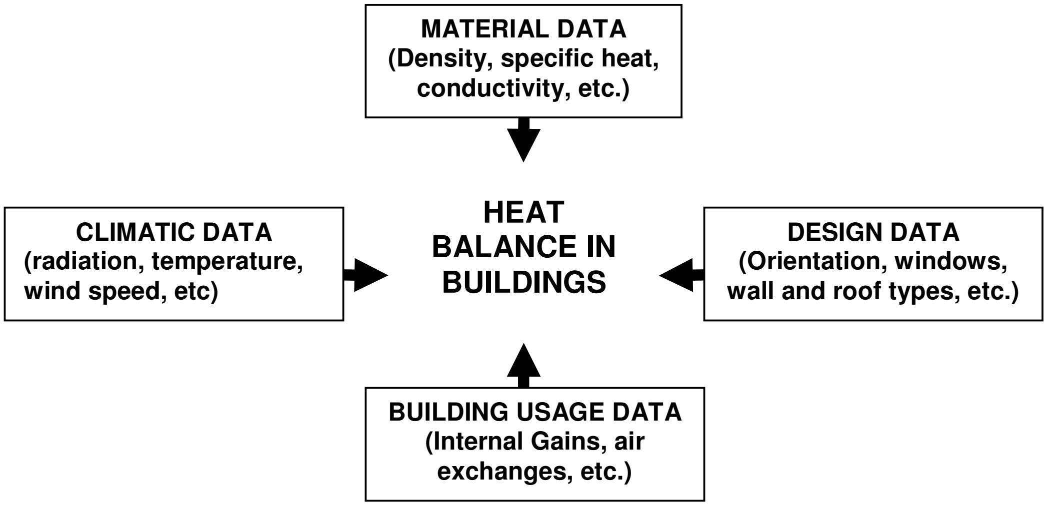

Fig. 4.3 Thermal simulation flow paths of a building

To understand the process of heat conduction, convection and radiation occurring in a building, consider a wall having one surface exposed to solar radiation and the other surface facing a room (Fig. 4.4). Of the total solar radiation incident on the outer surface of the wall, a part of it is reflected to the environment. The remaining part is absorbed by the wall and converted into heat energy. A part of the heat is again lost to the environment through convection and radiation from the wall's outer surface. The remaining part is conducted into the wall; where it is partly stored – thereby raising the wall temperature – while the rest reaches the room's interior surface. The inner surface transfers heat by convection and radiation to the room air, raising its temperature. Heat exchanges like these take place through opaque building elements such as walls and roofs. Additionally, mutual radiation exchanges between the inner surfaces of the building also occur (for example, between walls, or between a wall and roof). Such heat transfer processes affect the indoor temperature of a room and consequently, the thermal comfort experienced by its occupants.

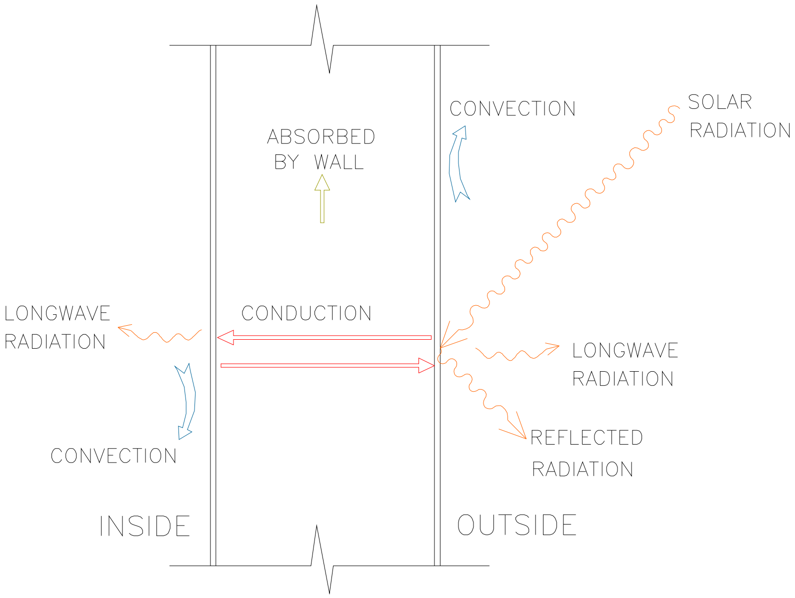

Fig. 4.4 Heat transfer processes occurring in a wall

Thus, a knowledge of the fundamentals of heat transfer and solar radiation would help in understanding the underlying processes that take place in a building and its interaction with the external environment. The reader can refer to the Glossary at the end of this book for definitions of unfamiliar terms. The reader may also like to refer to Koenisberger et al. [1] and Markus and Morris [2] for more information.

4.2 HEAT TRANSFER

In this section, we discuss the basic concepts on conduction, convection, radiation and evaporation.

4.2.1 Conduction

Thermal conduction is the process of heat transfer from one part of a body at a higher temperature to another (or between bodies in direct contact) at a lower temperature. This happens with negligible movement of the molecules in the body, because the heat is transferred from one molecule to another in contact with it. Heat can be conducted through solids, liquids and gases. Some materials conduct more rapidly than others. The basic equation of heat conduction is

$$Q_{conduction} = \frac{k\ A\ (T_h - T_c)}{L} \tag{4.1}$$

where $Q_{conduction}$ = quantity of heat flow (W)
k = thermal conductivity of the material (W/m-K)
A = area (m^2)
L = thickness (m)
T_h = temperature of the hot surface (K)
T_c = temperature of the cold surface (K)

For a given temperature difference, the higher the thermal conductivity of a material of fixed thickness and cross-sectional area, the greater is the quantity of heat transferred. Appendix IV.1 presents the values of thermal conductivity, density and specific heat of some building materials.

4.2.2 Convection

The convection is the transfer of heat from one part of a fluid (gas or liquid) to another part at a lower temperature by mixing of fluid particles. Heat transfer by convection takes place at the surfaces of walls, floors and roofs. Because of the temperature difference between the fluid and the contact surface, there is a density variation in the fluid, resulting in buoyancy. This results in heat exchange between the fluid and the surface and is known as free convection. However, if the motion of the fluid is due to external forces (such as wind), it is known as forced convection. These two processes could occur simultaneously. The rate of heat transfer ($Q_{convection}$) by convection from a surface of area A, can be written as

$$Q_{convection} = h\,A\,(T_s - T_f) \qquad (4.2)$$

where, h = heat transfer coefficient (W/m^2-K)

T_s = temperature of the surface (K)

T_f = temperature of the fluid (K)

The numerical value of the heat transfer coefficient depends on the nature of heat flow, velocity of the fluid, physical properties of the fluid, and the surface orientation.

4.2.3 Radiation

Radiation is the heat transfer from a body by virtue of its temperature; it increases as temperature of the body increases. It does not require any material medium for propagation. When two or more bodies at different temperatures exchange heat by radiation, heat will be emitted, absorbed and reflected by each body. The radiation exchange between two large parallel plane surfaces (of equal area A) at uniform temperatures T_1 and T_2 respectively, can be written as

$$Q_{12} = \varepsilon_{eff}\ A\ \sigma\,(T_1^4 - T_2^4) \qquad (4.3)$$

with $\varepsilon_{eff} = [\,1/\varepsilon_1 + 1/\varepsilon_2 - 1]^{-1}$

where Q_{12} = net radiative exchange between surfaces (W)

σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m^2-K^4)

A = area of surface (m^2)

T_1 = temperature of surface 1 (K)

T_2 = temperature of surface 2 (K)

ε_1 and ε_2 = emissivities of surfaces 1 and 2 respectively

In case of buildings, external surfaces such as walls and roofs are always exposed to the atmosphere. So the radiation exchange ($Q_{radiation}$) between the exposed parts of the building and the atmosphere is an important factor and is given by

$$Q_{radiation} = A\,\varepsilon\,\sigma\,(T_s^4 - T_{sky}^4) \qquad (4.4)$$

where A = area of the building exposed surface (m^2)

ε = emissivity of the building exposed surface

T_s = temperature of the building exposed surface (K)

T_{sky} = sky temperature (K)

T_{sky} represents the temperature of an equivalent atmosphere. It considers the fact that the atmosphere is not at a uniform temperature, and that the atmosphere radiates only in certain wavelengths. There are many correlations suggested for expressing sky temperature in terms of ambient air temperature.

Equation (4.4) can be written as:

$$\frac{Q_{radiation}}{A} = h_r (T_s - T_a) + \varepsilon \Delta R \qquad (4.5)$$

where T_a = ambient temperature (K)

$$h_r = \varepsilon \sigma (T_s^4 - T_a^4)/(T_s - T_a) \qquad (4.6)$$

h_r is the radiative heat transfer coefficient, and ΔR is the difference between the long wavelength radiation incident on the surface from the sky and the surroundings, and the radiation emitted by a black body at ambient temperature. For horizontal surface, ΔR can be taken as 63 W/m^2 and for a vertical surface, it is zero [3].

For building applications, usually convective and radiative heat transfer coefficients are combined to define surface heat transfer coefficient. Table 4.1 presents values of the surface heat transfer coefficient for a few cases [4].

Table 4.1 Values of surface heat transfer coefficient [4]

Serial No.	Wind Speed	Position of Surface	Direction of Heat Flow	Surface Heat Transfer Coefficient (W/m^2-K)
1.	Still air	Horizontal	Up	9.3
		Sloping 45°	Up	9.1
		Vertical	Horizontal	8.3
		Sloping 45°	Down	7.5
		Horizontal	Down	6.1
2.	Moving air 12 (km/h)	Any position	Any direction	22.7
	Moving air 24 (km/h)	Any position	Any direction	34.1

4.2.4 Evaporation

Evaporation generally refers to the removal of water by vaporisation from aqueous solutions of non-volatile substances. It takes place continuously at all temperatures and increases as the temperature is raised. Increase in the wind speed also causes increased rates of evaporation. The latent heat required for vapourisation is taken up partly from the surroundings and partly from the liquid itself. Evaporation thus causes cooling.

The rate of evaporation depends on:

- the temperature (rate of evaporation increases with increase in temperature)
- the area of the free surface of water (larger the surface exposed, greater is this rate)
- the wind (rate is faster when wind blows than when the air is still)
- the pressure (lower the external pressure, more rapid is the evaporation)

4.3 SOLAR RADIATION

The sun is the only source of heat and light for the entire solar system. It is made up of extremely hot gaseous matter, and gets progressively hotter towards its centre. The heat is generated by various kinds of fusion reactions. The sun is approximately spherical in shape, about 1.39×10^6 km in diameter and its average distance from the earth is 1.496×10^8 km (Fig. 4.5). The solar disc subtends a very small angle of 32' at any point on the earth's surface and hence, the radiation received from the sun directly on the earth's surface can be considered parallel for all practical purposes.

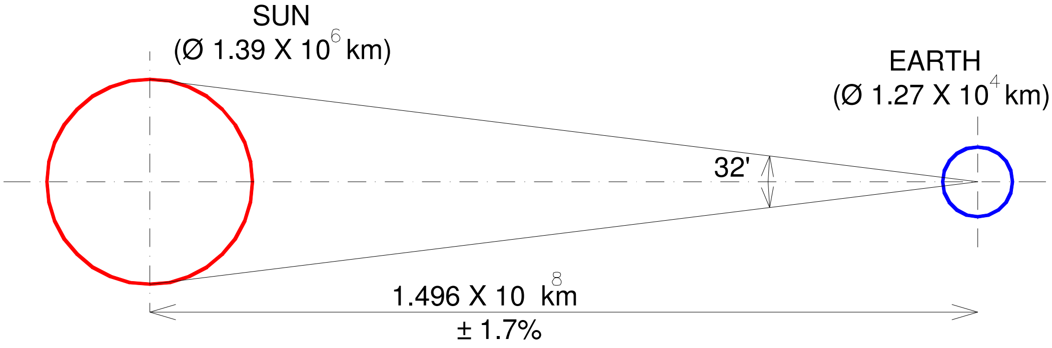

Fig. 4.5 Sun-Earth geometric relationship

The earth is approximately spherical in shape, about 1.27×10^4 km in diameter. It revolves around the sun in an elliptical orbit taking a year to complete one revolution. At the same time, it also rotates about its own axis once every 24 hours. The energy flux received from the sun outside the earth's atmosphere is of nearly constant value and is termed as the Solar Constant (I_{sc}). It is defined as the energy received outside the atmosphere, per second, by a unit surface area normal to the direction of sun's rays at the mean sun-earth distance; its value is accepted as 1367 W/m^2. However, because the earth revolves round the sun in an elliptical orbit with the sun as one of the foci, there is a variation in the extraterrestrial radiation. Hence, the intensity of extraterrestrial radiation on a plane normal to sun's rays on any day is given by:

$$I_{ext} = I_{sc}\left[1.0 + 0.033\cos(360n/365)\right] \qquad (4.7)$$

where n is the day of the year and is

$$1 \le n \le 365 \qquad (4.8)$$

Solar radiation is received on the earth's surface after undergoing various mechanisms of attenuation, reflection and scattering in the earth's atmosphere. Consequently, two types of radiation are received at the earth's surface: one that is received from the sun without change of direction, called *beam radiation*, and the other whose direction has been changed by scattering and reflection, called *diffuse radiation*. The sum of these two types is known as total or global radiation.

Usually solar radiation incident on the earth's surface is measured on a horizontal surface. Both global and diffuse radiation are recorded at a number of places in India. In order that the data reflect a true representation of the place, hourly measurements are carried out for a large number of years (typically ten years), and monthly averages of hourly radiation values over a number of years are calculated. Such data are available in various handbooks [e.g., Reference 5].

4.3.1 Radiation on Tilted Surfaces

External surfaces of buildings receiving solar radiation are generally tilted, except for the flat roof, which is a horizontal surface. Consequently, it is required to estimate radiation on such surfaces from the data measured on a horizontal surface.

A tilted surface receives three types of solar radiation, namely beam radiation directly from the sun, diffuse radiation coming from the sky dome, and reflected radiation due to neighbouring buildings and objects. The estimation of the last component is very complicated. However, its contribution is much less compared to the first two sources. Therefore, the reflected component from the surrounding ground surface is generally taken for simple calculations. However, simulation software like DOE2.1E [6] performs a more detailed calculation for accounting the effects of neighbouring buildings and trees.

4.3.1.1 Unshaded surface

For a surface tilted at an angle β and with no shading, hourly incident solar radiation can be estimated as:

$$I_T = I_g r \tag{4.9}$$

where r is the global radiation tilt factor and is given by [7]

$$r = (1 - \frac{I_d}{I_g})\, r_b + (\frac{1+\cos\beta}{2})\frac{I_d}{I_g} + \rho(\frac{1-\cos\beta}{2})$$

$$r_b = \frac{\cos\theta}{\cos\theta_z}$$

$$\begin{aligned}\cos\theta &= \sin\phi\,(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta)\\ &\quad + \cos\phi\,(\cos\delta\cos\omega\cos\beta - \sin\delta\cos\gamma\sin\beta)\\ &\quad + \cos\delta\sin\gamma\sin\omega\sin\beta)\end{aligned}$$

$$\cos\theta_z = \sin\phi\sin\delta + \cos\phi\cos\delta\cos\omega$$

(4.10)

I_g = mean hourly global solar radiation (W/m^2)
I_d = mean hourly diffuse solar radiation (W/m^2)
ρ = reflectivity of the ground surface
ϕ = latitude of a location (degree). By convention, the latitude is measured as positive

for the northern hemisphere.

δ = declination angle (degree). It is defined as the angle made by the line joining the centres of the sun and the earth with its projection on the equatorial plane. It can be calculated from the following relation:

$$\delta(\text{in degrees}) = 23.45 \sin\left[\frac{360}{365}(284+n)\right] \qquad (4.11)$$

n = day of the year

γ = surface azimuth angle (degree). It is the angle made in the horizontal plane between the line due south, and the projection of the normal to the surface on the horizontal plane. By convention, the angle is taken to be positive if the normal is east of south and negative if west of south.

β = slope (degree). It is the angle made by the plane surface with the horizontal.

ω = hour angle (degree). It is the angular measure of time and is equivalent to 15° per hour. It is measured from noon based on local apparent time (LAT), being positive in the morning and negative in the afternoon.

The local apparent time (LAT) can be estimated from Indian Standard Time (IST) using the following equation:

$$\text{LAT} = \text{IST} - 4\,(\text{Reference longitude} - \text{Local longitude}) + \text{ET} \qquad (4.12)$$

The second term in the equation becomes positive for any country in the western hemisphere. The reference longitude for India is 82.5^0 E. The Equation of Time (ET) correction is plotted in Fig. 4.6 and it can also be calculated from:

$$\text{ET} = 229.2\,(0.000075 + 0.001868\cos B - 0.032077\sin B - 0.014615\cos 2B - 0.04089\sin 2B) \qquad (413)$$

where B = (n - 1) 360/365 and n is the day of the year.

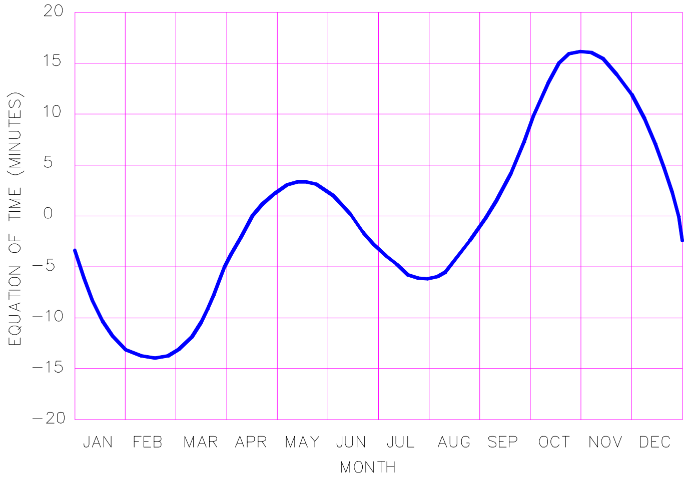

Fig. 4.6 Equation of time correction [4]

Equation (4.9) can be used to calculate hourly radiation on any tilted surface. The values for mean hourly global and diffuse solar radiation on horizontal, and global radiation on vertical surfaces (south, north, east and west) for some Indian cities during the months of May and December are presented in Appendix IV.2. The appendix also lists hourly ambient temperature for these months.

4.3.1.2 Shaded surface

If a surface is shaded, the radiation incident on it gets modified, and depending on the type of shading, its estimation becomes complicated. To illustrate, let us consider the simple case of a horizontal rectangular overhang on a wall (Fig. 4.7). The height and width of the wall are H and W respectively, the depth of the overhang is P.

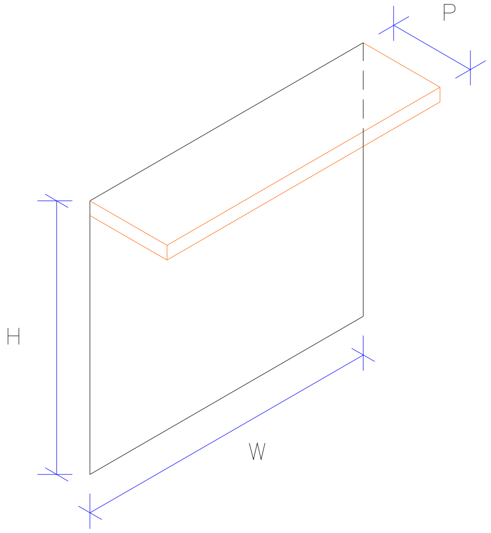

Fig. 4.7 Horizontal rectangular overhang on a wall

Hourly solar radiation on the wall can be written as:

$$I_T = I_g\, r \tag{4.14}$$

where $$r = (1 - \frac{I_d}{I_g})\, r_b\, f_i + \frac{I_d}{I_g} F_{r-s} + 0.5\, \rho \tag{4.15}$$

f_i = fraction of unshaded area
and F_{r-s} = view factor of the wall for radiation from the sky.

f_i is given by

$$f_i = \frac{A_i}{WH} \tag{4.16}$$

A_i is the unshaded area of the wall and is given by

$$A_i = W\,H - A_{shade} \tag{4.17}$$

The shaded area (A_{shade}) of the wall at any time, on any day is given by:

$$A_{shade} = \left[W - 0.5P\tan(\gamma_s - \gamma)\right] P\ \tan(90 - \theta_z)\ \sec(\gamma_s - \gamma) \tag{4.18}$$

γ_s = solar azimuth angle (degree). It is the angle made in the horizontal plane between the line due south, and the projection of the sun's rays on the horizontal plane. By convention, the angle is positive if the normal is east of south, and negative if west of south. It is given by:

$$\cos\gamma_s = (\cos\theta_z\ \sin\phi - \sin\delta)/\sin\theta_z\ \cos\phi \tag{4.19}$$

$F_{r\text{-}s}$ for a wall of relative width w (= W/H) and relative projection p (= P/H) is presented in Table 4.2 [8].

Table 4.2 Wall radiation view factor for the sky, $F_{r\text{-}s}$ [8]

w	$F_{r\text{-}s}$ at p=								
	0.10	0.20	0.30	0.40	0.50	0.75	1.00	1.50	2.00
1.0	0.46	0.42	0.40	0.37	0.35	0.32	0.30	0.28	0.27
4.0	0.46	0.41	0.38	0.35	0.32	0.27	0.23	0.19	0.16
25.0	0.45	0.41	0.37	0.34	0.31	0.25	0.21	0.15	0.12

4.4 SIMPLIFIED METHOD FOR PERFORMANCE ESTIMATION

Based on the concepts discussed in previous sections, we can calculate the various heat exchanges (Fig. 4.1) taking place in a building.

4.4.1 Conduction

The rate of heat conduction (Q_{cond}) through any element such as roof, wall or floor under steady state can be written as

$$Q_{cond} = A\ U\ \Delta T \tag{4.20}$$

where,

A = surface area (m^2)
U = thermal transmittance ($W/\ m^2$- K)
ΔT = temperature difference between inside and outside air (K)

It may be noted that the steady state method does not account for the effect of heat capacity of building materials.

U is given by

$$U = \frac{1}{R_T} \tag{4.21}$$

where R_T is the total thermal resistance and is given by

$$R_T = \frac{1}{h_i} + \left(\sum_{j=1}^{m} L_j / k_j \right) + \frac{1}{h_o} \tag{4.22}$$

h_i and h_o respectively, are the inside and outside heat transfer coefficients. L_j is the thickness of the j^{th} layer and k_j is the thermal conductivity of its material.

U indicates the total amount of heat transmitted from outdoor air to indoor air through a given wall or roof per unit area per unit time. The lower the value of U, the higher is the insulating value of the element. Thus, the U-value can be used for comparing the insulating values of various building elements. Examples showing calculation of U-values for a few typical cases are presented in Appendix IV.3.

Equation (4.20) is solved for every external constituent element of the building i.e., each wall, window, door, roof and the floor, and the results are summed up. The heat flow rate through the building envelope by conduction, is the sum of the area and the U-value products of all the elements of the building multiplied by the temperature difference. It is expressed as:

$$Q_c = \sum_{i=1}^{N_c} A_i U_i \Delta T_i \tag{4.23}$$

where,

i = building element
N_c = number of components

If the surface is also exposed to solar radiation then,

$$\Delta T = T_{so} - T_i \tag{4.24}$$

where T_i is the indoor temperature; T_{so} is the sol-air temperature, calculated using the expression:

$$T_{so} = T_o + \frac{\alpha S_T}{h_o} - \frac{\varepsilon \Delta R}{h_o} \tag{4.25}$$

where,

T_o = daily average value of hourly ambient temperature (K)
α = absorptance of the surface for solar radiation
S_T = daily average value of hourly solar radiation incident on the surface (W/m^2)
h_o = outside heat transfer coefficient (W/m^2 -K)

ε = emissivity of the surface

ΔR = difference between the long wavelength radiation incident on the surface from the sky and the surroundings, and the radiation emitted by a black body at ambient temperature

Values of heat transfer coefficient (h_o) at different wind speeds and orientation are presented in Table 4.1. The absorptance values of some common building surfaces are given in Appendix IV.4.

Daily average values of hourly solar radiation can be calculated from the hourly data. As mentioned earlier, measurements of global and diffuse solar radiation are carried out on a horizontal surface. Mean hourly values of such data for various places in India are available in the handbook by Mani [5]. Hourly radiation on a tilted surface can be estimated from these data using Eq. (4.9) for unshaded surfaces or Eq. (4.13) for shaded surfaces.

4.4.2 Ventilation

The heat flow rate due to ventilation of air between the interior of a building and the outside, depends on the rate of air exchange. It is given by:

$$Q_v = \rho \, V_r \, C \, \Delta T \qquad (4.26)$$

where,

ρ = density of air (kg/ m^3)

V_r = ventilation rate (m^3/ s)

C = specific heat of air (J/ kg-K)

ΔT = temperature difference ($T_o - T_i$) (K)

Table 4.3 Recommended air change rates [4]

Space to be ventilated	Air changes per hour
Assembly hall/ Auditorium (smoking)	3-6
Bedrooms / Living rooms (smoking)	3-6
Bathrooms/ Toilets	6-12
Cafes/Restaurants (smoking)	12-15
Cinemas/Theatres (non –smoking)	6-9
Classrooms	3-6
Factories(medium metal work - smoking)	3-6
Garages (smoking)	12-15
Hospital wards (smoking)	3-6
Kitchens (common - smoking)	6-9
Kitchens (Domestic - smoking)	3-6
Laboratories	3-6
Offices (smoking)	3-6

If the number of air changes is known, then

$$V_r = \frac{NV}{3600} \tag{4.27}$$

where,

N = number of air changes per hour
V = volume of the room or space (m^3)

Thus,

$$Q_v = \rho\, C\, \frac{NV}{3600}\, \Delta T \tag{4.28}$$

The minimum standards for ventilation in terms of air changes per hour (N) are presented in Table 4.3.

4.4.3 Solar Heat Gain

The solar gain through transparent elements can be written as:

$$Q_s = \alpha_s \sum_{i=1}^{M} A_i\, S_{gi}\, \tau_i \tag{4.29}$$

where,

α_s = mean absorptivity of the space
A_i = area of the ith transparent element (m^2)
S_{gi} = daily average value of solar radiation (including the effect of shading) on the ith transparent element (W/m^2)
τ_i = transmissivity of the ith transparent element
M = number of transparent elements

4.4.4 Internal Gain

The internal heat gain of a building is estimated as follows:

- The heat generated by occupants is a heat gain for the building; its magnitude depends on the level of activity of a person. Table 4.4 shows the heat output rate of human bodies for various activities [9]. The total rate of energy emission by electric lamps is also taken as internal heat gain. A large part of this energy is emitted as heat (about 95% for ordinary incandescent lamps and 79% for fluorescent lamps) and the remaining part is emitted as light, which when incident on surfaces, is converted into heat. Consequently, the total wattage of all lamps in the building when in use, must be added to the Q_i.

- The heat gain due to appliances (televisions, radios, etc.) should also be added to the Q_i. If an electric motor and the machine driven by it are both located (and operating) in the same space, the total wattage of the motor must be included. If the horse power (hp) of a motor is known, its corresponding wattage can be calculated by multiplying it by 746 (1 hp = 746 W). If the motor alone is in the space considered, and if efficiency is M_{eff}, then energy release into the space is 746 (1-M_{eff}) hp. The load due to common household appliances is listed in Table 4.5 [9].

Table 4.4 Heat production rate in a human body [9]

Activity	Rate of heat production	
	(W)	(W/m^2)
Sleeping	60	35
Resting	80	45
Sitting, Normal office work	100	55
Typing	150	85
Slow walking(3 km/h)	200	110
Fast walking(6 km/h)	250	140
Hard work(filing, cutting, digging, etc.)	more than 300	More than 170

Table 4.5 Wattage of common household appliances [9]

Equipment	Load (W)
Radio	15
Television(black/white)	110
Refrigerator	120
Television(colour)	250
Coffee machine	400
Vacuum cleaner	800
Washing machine	2500
Dishwasher	3050
Water heater	3500

Thus the heat flow rate due to internal heat gain is given by the equation:

$$Q_i = (\text{No. of people} \times \text{heat output rate}) + \text{Rated wattage of lamps} + \text{Appliance load} \quad (4.30)$$

4.4.5 Evaporation

The rate of cooling by evaporation (Q_{ev}) from, say, a roof pond, fountains or human perspiration, can be written as:

$$Q_{ev} = m\,L \quad (4.31)$$

where m is the rate of evaporation (kg/s) and L is the latent heat of evaporation (J/kg-K)

4.4.6 Equipment Gain

If any mechanical heating or cooling equipment is used, the heat flow rate of the equipment is added to the heat gain of the building.

4.5 EXAMPLE

Suppose we have a room that is 5 m long, 4 m wide and 3 m high, as shown in Fig. 4.8. If the room is maintained at 23.3°C by an air-conditioner, how may we calculate the load on the appliance using the steady state approach?

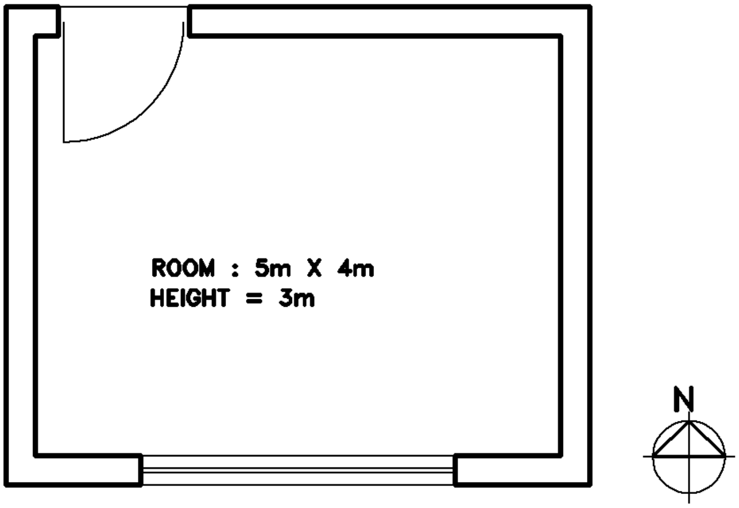

Fig. 4.8 Plan of a single zone room

We have the following data available:

Place: New Delhi
Month: May
Ventilation rate: 2 h^{-1}
Artificial light: Three 100 W bulbs continuously used
Occupants: Four persons (normal office work; 24 hours occupancy)
Window: (1.5m X 3m) on south wall, single glazed
Door: (1.2m X 2m) on north wall
$U_{glazing} = 5.77$ W/m^2-K
$U_{wall} = 3.00$ W/m^2-K
$U_{roof} = 2.31$ W/m^2-K
$U_{door} = 3.18$ W/m^2-K
Daily average outside temperature in May: 32.7 ºC [Appendix IV.2]
Absorptance of external wall surfaces: 0.6
Outside heat transfer coefficient: 22.7 W/m^2-K
Inside design temperature: 23.3 ºC

Daily average solar radiation on south wall: 111.3 W/m^2
Daily average solar radiation on east wall: 158.2 W/m^2
Daily average solar radiation on north wall: 101.1 W/m^2
Daily average solar radiation on west wall: 155.2 W/m^2
Daily average solar radiation on roof: 303.1 W/m^2
Daily average solar radiation on window: 111.3 W/m^2 (no shading)
Mean absorptivity of the space: 0.6
Transmissivity of window: 0.86
Absorptivity of glazing for solar radiation: 0.06
Absorptivity of wood for solar radiation: 0.0
Density of air: 1.2 kg/m^3
Specific heat of air: 1005 J/ kg-K

Under the steady state approach (which does not account the effect of heat capacity of building materials), the heat balance for room air can be written as

$$Q_{total} = Q_c + Q_s + Q_i + Q_v \qquad (4.32)$$

From Eq. (4.25), with $\Delta R = 0$ for vertical surfaces, the values of sol-air temperatures are:

$$T_{so}^{south} = 32.7 + (0.6 \text{ x } \frac{111.3}{22.7}) = 35.6 \text{ °C}$$

Similarly, $T_{so}^{east} = 36.9$ °C , $T_{so}^{north} = 35.4$ °C , $T_{so}^{west} = 36.8$ °C , $T_{so}^{door} = 32.7$ °C and $T_{so}^{glazing} = 33.0$ °C

For the roof, $\Delta R = 63$ W/ m^2 and hence $T_{so}^{roof} = 38.2$ °C

$$\begin{aligned} Q_c &= 3.00\ (15 - 4.5)\ (35.6 - 23.3) + 3.00 \text{ x } 12\ (36.9 - 23.3) + 3.00\ (15 - 2.4)\ (35.4 - 23.3) \\ &\quad + 3.00 \text{ x } 12\ (36.8 - 23.3) + 3.18 \text{ x } 2.4\ (32.7 - 23.3) + 2.31 \text{ x } 20\ (38.2 - 23.3) \\ &\quad + 5.77 \text{ x } 4.5\ (33.0 - 23.3) \\ &= 2832.4 \text{ W} \end{aligned}$$

Using Eqs. (4.26 – 4.30),
$Q_s = 0.6 \text{ x } 4.5 \text{ x } 111.3 \text{ x } 0.86 = 258.4$ W
$Q_i = 3 \text{ x } 100 + 4 \text{ x } 100 = 700$ W
$Q_v = 1.2 \text{ x } 1005\ (2 \text{ x } 5 \text{ x } 4 \text{ x } 3/3600)\ (32.7 - 23.3) = 377.9$ W

Thus, $Q_m = 2832.4 + 258.4 + 700 + 377.9 = 4168.7 \approx 4.2$ kW

Remarks: Now, the problem facing a designer is to make sense of this quantity. As the total heat gain rate is positive; it represents the total heat entering the building. How does 4.2 kW translate practically? Let us consider it from two angles.

- The COP of a standard window air conditioner of 1.5 tons cooling capacity is about 2.8. So the power required is 1.5 kW (i.e., 4.2 kW/2.8)

- Suppose the machine were to be used for 8 hours a day; then it would consume 12 kWh per day (1.5 kW × 8 hours = 12) or 12 units (One kWh is equivalent to one unit) of electricity supplied by the power company. At a rate of Rs. 4 per unit, expenses would amount to Rs. 48 per day.

4.6 COMPUTER-BASED TOOLS

The above example illustrates the steady state calculation of heat gain or loss for a single zone conditioned building. The method can also be extended to multi-zone or multi-storeyed buildings, but the algebra becomes complicated. Besides, the effects of: (a) variation of outside air temperature and solar radiation with time, (b) shading by neighbouring objects, (c) self shading, and (d) thermal capacity of the building (i.e. the ability of building materials to store heat during daytime and release it back to the environment later) add to the complexity of the calculations. Consequently, one resorts to computer-based tools known as building simulation tools. A number of such tools are now available to do quick and accurate assessment of a building's thermal and daylighting performance. These tools can estimate the performances of different designs of the building for a given environmental condition. From these results, a designer can choose the design that consumes minimum energy. Thermal calculations also help to select appropriate retrofits for existing buildings from the viewpoint of energy conservation. Thus, by integrating the simulation of thermal performance of a building with its architectural design, one can achieve an energy efficient building.

A number of tools are available for simulating the thermal performance of buildings; they address different needs. For example, an architect's office requires a tool that is quick and gets well integrated into the design process. On the other hand an HVAC engineer would look for a tool that would accurately predict the energy a building would consume, for optimum sizing of the air-conditioning systems. A short description of a few simulation tools is provided in Appendix IV.5. The reader may also refer to internet websites (such as http://www.energytoolsdirectory.gov) for more information.

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APPENDIX IV.1

PROPERTIES OF BUILDING MATERIALS [4]

Material	Density (kg/m^3)	Specific heat (kJ/kg-K)	Thermal conductivity (W/m-K)
Burnt brick	1820	0.88	0.811
Mud brick	1731	0.88	0.750
Dense concrete	2410	0.88	1.740
RCC	2288	0.88	1.580
Limestone	2420	0.84	1.800
Slate	2750	0.84	1.720
Reinforced concrete	1920	0.84	1.100
Brick tile	1892	0.88	0.798
Lime concrete	1646	0.88	0.730
Mud phuska	1622	0.88	0.519
Cement mortar	1648	0.92	0.719
Cement plaster	1762	0.84	0.721
Cinder concrete	1406	0.84	0.686
Foam slag concrete	1320	0.88	0.285
Gypsum plaster	1120	0.96	0.512
Cellular concrete	704	1.05	0.188
AC sheet	1520	0.84	0.245
GI sheet	7520	0.50	61.060
Timber	480	1.68	0.072
Plywood	640	1.76	0.174
Glass	2350	0.88	0.814
Sand	2240	0.84	1.740
Expanded polystyrene	34	1.34	0.035
Foam glass	160	0.75	0.055
Foam concrete	704	0.92	0.149
Rock wool (unbonded)	150	0.84	0.043
Mineral wool (unbonded)	73.5	0.92	0.030
Glass wool (unbonded)	189	0.92	0.040
Resin bonded mineral wool	99	1.00	0.036
Resin bonded glass wool	24	1.00	0.036
Asbestos mill board	1397	0.84	0.249
Hard board	979	1.42	0.279
Straw board	310	1.30	0.057
Soft board	249	1.30	0.047
Wall board	262	1.26	0.047
Chip board	432	1.26	0.067
Particle board	750	1.30	0.098
Coconut pith insulation board	520	1.09	0.060
Jute fibre	329	1.09	0.067
Wood wool board (bonded with cement)	674	1.13	0.108
Coir board	97	1.00	0.038
Saw dust	188	1.00	0.051
Rice husk	120	1.00	0.051
Aluminium Composite panels (Alucopan – 150)*	150	0.902	0.060
Face bricks*	2083	1.004	1.30
Polycarbonate sheet*	1350	1.17	0.21
Fly ash brick*	1570	0.8	0.54 to 0.70
Fibre reinforced plastic (FRP) sheet (Durostone standard)*	1850	0.96	0.260

Polyurethane foam (PUF)*	30	1.570	0.026
Polyvinyl chloride sheet*	1350	1.255	0.160
Cork tile*	540	1.00	0.085
Plastic tile*	1050	1.07	0.50
PVC asbestos tile*	2000	1.00	0.85
Gypsum plasterboard*	950	0.82	0.16
Brown cellulose fibres*	37-51	1.35	0.045
Thatch (reed)*	270	1.00	0.09
Thatch (straw)*	240	1.00	0.07
Acoustic tile*	290	1.34	0.058

* compiled from various websites.

APPENDIX - IV.2

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(A) Place: Jodhpur (26^o 18’N, 73^o 01’E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^2)					Ambient temperature (^oC) [5]	Solar radiation (kW/m^2)					Ambient Temperature (^oC) [5]
	Horizontal surface [5]	South surface	East surface	North surface	West surface		Horizontal surface [5]	South surface	East surface	North surface	West surface	
6	0.024	0.012	0.012	0.012	0.012	28.1	0.000	0.000	0.000	0.000	0.000	13.3
7	0.175	0.070	0.332	0.135	0.070	27.1	0.005	0.002	0.002	0.002	0.002	12.9
8	0.393	0.130	0.525	0.188	0.130	29.5	0.110	0.268	0.428	0.033	0.033	12.9
9	0.603	0.176	0.599	0.195	0.176	31.9	0.311	0.487	0.577	0.073	0.073	14.4
10	0.771	0.234	0.568	0.207	0.207	34.0	0.491	0.646	0.553	0.100	0.100	16.5
11	0.892	0.292	0.468	0.226	0.226	36.1	0.613	0.735	0.417	0.118	0.118	19.6
12	0.953	0.321	0.319	0.234	0.234	37.7	0.676	0.779	0.232	0.128	0.128	22.6
13	0.951	0.322	0.236	0.236	0.320	39.1	0.677	0.778	0.129	0.129	0.232	24.4
14	0.884	0.291	0.226	0.226	0.464	40.0	0.613	0.732	0.120	0.120	0.416	25.4
15	0.751	0.236	0.210	0.210	0.550	40.4	0.484	0.632	0.101	0.0101	0.542	25.6
16	0.577	0.177	0.177	0.194	0.562	40.4	0.307	0.481	0.072	0.072	0.570	25.4
17	0.362	0.127	0.127	0.177	0.464	40.3	0.109	0.265	0.033	0.033	0.421	24.8
18	0.157	0.066	0.066	0.118	0.277	39.6	0.005	0.002	0.002	0.002	0.002	22.9
19	0.020	0.011	0.011	0.033	0.070	38.5	0.000	0.000	0.000	0.000	0.000	20.7
20	0.000	0.000	0.000	0.000	0.000	37.1	0.000	0.000	0.000	0.000	0.000	19.5
21	0.000	0.000	0.000	0.000	0.000	35.6	0.000	0.000	0.000	0.000	0.000	18.6
22	0.000	0.000	0.000	0.000	0.000	34.5	0.000	0.000	0.000	0.000	0.000	17.9
23	0.000	0.000	0.000	0.000	0.000	33.6	0.000	0.000	0.000	0.000	0.000	16.4
24	0.000	0.000	0.000	0.000	0.000	32.7	0.000	0.000	0.000	0.000	0.000	16.3
1	0.000	0.000	0.000	0.000	0.000	31.9	0.000	0.000	0.000	0.000	0.000	15.6
2	0.000	0.000	0.000	0.000	0.000	31.1	0.000	0.000	0.000	0.000	0.000	15.1
3	0.000	0.000	0.000	0.000	0.000	30.2	0.000	0.000	0.000	0.000	0.000	14.5
4	0.000	0.000	0.000	0.000	0.000	29.6	0.000	0.000	0.000	0.000	0.000	14.1
5	0.000	0.000	0.000	0.000	0.000	28.9	0.000	0.000	0.000	0.000	0.000	13.7

LAT: Local Apparent Time

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(B) Place: New Delhi (28^{o} 35’N, 77^{o} 12’E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^{2})					Ambient temperature (^{o}C) [5]	Solar radiation (kW/m^{2})					Ambient Temperature (^{o}C) [5]
	Horizontal surface [5]	South surface	East surface	North surface	West surface		Horizontal surface [5]	South surface	East surface	North surface	West surface	
6	0.030	0.017	0.017	0.017	0.017	26.3	0.000	0.000	0.000	0.000	0.000	9.7
7	0.177	0.075	0.300	0.128	0.075	27.1	0.003	0.001	0.002	0.001	0.001	9.5
8	0.383	0.133	0.491	0.178	0.133	29.3	0.085	0.199	0.310	0.031	0.031	9.8
9	0.581	0.180	0.563	0.184	0.180	31.8	0.259	0.407	0.472	0.072	0.072	12.3
10	0.746	0.258	0.545	0.214	0.214	34.1	0.425	0.565	0.477	0.104	0.104	14.9
11	0.865	0.321	0.459	0.238	0.238	35.7	0.543	0.662	0.378	0.126	0.126	17.3
12	0.925	0.354	0.327	0.250	0.250	36.9	0.605	0.710	0.226	0.138	0.138	19.0
13	0.920	0.353	0.251	0.251	0.327	37.7	0.605	0.709	0.139	0.139	0.226	20.1
14	0.844	0.317	0.238	0.238	0.449	38.3	0.538	0.652	0.127	0.127	0.374	20.7
15	0.719	0.256	0.215	0.215	0.522	38.5	0.418	0.552	0.104	0.104	0.466	20.9
16	0.547	0.178	0.178	0.181	0.519	38.7	0.255	0.399	0.072	0.072	0.462	20.7
17	0.352	0.130	0.130	0.168	0.432	38.0	0.086	0.211	0.030	0.030	0.330	19.7
18	0.158	0.069	0.069	0.113	0.252	37.5	0.003	0.002	0.001	0.001	0.001	17.2
19	0.027	0.014	0.014	0.051	0.117	35.9	0.000	0.000	0.000	0.000	0.000	15.9
20	0.000	0.000	0.000	0.000	0.000	34.1	0.000	0.000	0.000	0.000	0.000	14.7
21	0.000	0.000	0.000	0.000	0.000	32.6	0.000	0.000	0.000	0.000	0.000	13.9
22	0.000	0.000	0.000	0.000	0.000	31.5	0.000	0.000	0.000	0.000	0.000	13.2
23	0.000	0.000	0.000	0.000	0.000	30.7	0.000	0.000	0.000	0.000	0.000	12.5
24	0.000	0.000	0.000	0.000	0.000	29.9	0.000	0.000	0.000	0.000	0.000	11.9
1	0.000	0.000	0.000	0.000	0.000	29.1	0.000	0.000	0.000	0.000	0.000	11.5
2	0.000	0.000	0.000	0.000	0.000	28.4	0.000	0.000	0.000	0.000	0.000	11.1
3	0.000	0.000	0.000	0.000	0.000	27.8	0.000	0.000	0.000	0.000	0.000	10.6
4	0.000	0.000	0.000	0.000	0.000	27.2	0.000	0.000	0.000	0.000	0.000	10.3
5	0.000	0.000	0.000	0.000	0.000	26.7	0.000	0.000	0.000	0.000	0.000	10.1

LAT: Local Apparent Time

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(C) Place: Mumbai (19° 07'N, 72° 51'E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^2)					Ambient temperature (^{o}C) [5]	Solar radiation (kW/m^2)					Ambient Temperature (^{o}C) [5]
	Horizontal surface [5]	South surface	East surface	North surface	West surface		Horizontal surface [5]	South surface	East surface	North surface	West surface	
6	0.012	0.006	0.006	0.006	0.006	27.2	0.000	0.000	0.000	0.000	0.000	20.3
7	0.124	0.056	0.212	0.100	0.056	27.5	0.013	0.006	0.006	0.006	0.006	20.1
8	0.294	0.115	0.354	0.166	0.115	28.9	0.142	0.237	0.381	0.045	0.045	21.1
9	0.489	0.166	0.461	0.211	0.166	30.4	0.342	0.425	0.535	0.080	0.080	24.2
10	0.710	0.205	0.518	0.237	0.205	31.2	0.517	0.546	0.511	0.108	0.108	26.4
11	0.864	0.226	0.453	0.238	0.226	31.9	0.647	0.627	0.399	0.129	0.129	28.3
12	0.952	0.238	0.319	0.236	0.236	32.3	0.717	0.669	0.235	0.140	0.140	29.6
13	0.962	0.235	0.233	0.233	0.319	32.4	0.719	0.670	0.141	0.141	0.236	30.3
14	0.899	0.219	0.219	0.232	0.468	32.4	0.652	0.630	0.132	0.132	0.402	30.5
15	0.768	0.195	0.195	0.233	0.571	32.3	0.524	0.551	0.112	0.112	0.516	30.1
16	0.578	0.157	0.157	0.225	0.595	31.9	0.353	0.436	0.084	0.084	0.549	29.5
17	0.360	0.113	0.113	0.198	0.517	31.5	0.155	0.269	0.046	0.046	0.437	28.2
18	0.150	0.058	0.058	0.134	0.328	30.7	0.017	0.007	0.007	0.007	0.007	26.6
19	0.017	0.007	0.007	0.007	0.007	29.9	0.000	0.000	0.000	0.000	0.000	25.6
20	0.000	0.000	0.000	0.000	0.000	29.5	0.000	0.000	0.000	0.000	0.000	25.0
21	0.000	0.000	0.000	0.000	0.000	29.1	0.000	0.000	0.000	0.000	0.000	24.3
22	0.000	0.000	0.000	0.000	0.000	28.9	0.000	0.000	0.000	0.000	0.000	23.5
23	0.000	0.000	0.000	0.000	0.000	28.7	0.000	0.000	0.000	0.000	0.000	22.7
24	0.000	0.000	0.000	0.000	0.000	28.4	0.000	0.000	0.000	0.000	0.000	21.9
1	0.000	0.000	0.000	0.000	0.000	28.2	0.000	0.000	0.000	0.000	0.000	21.4
2	0.000	0.000	0.000	0.000	0.000	28.0	0.000	0.000	0.000	0.000	0.000	21.0
3	0.000	0.000	0.000	0.000	0.000	27.7	0.000	0.000	0.000	0.000	0.000	20.7
4	0.000	0.000	0.000	0.000	0.000	27.5	0.000	0.000	0.000	0.000	0.000	20.5
5	0.000	0.000	0.000	0.000	0.000	27.4	0.000	0.000	0.000	0.000	0.000	20.4

LAT: Local Apparent Time

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(D) Place: Pune (18^{o} 32’N, 73^{o} 51’E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^2)					Ambient temperature (^{o}C) [5]	Solar radiation (kW/m^2)					Ambient Temperature (^{o}C) [5]
	Horizontal surface [5]	South surface	East surface	North surface	West surface		Horizontal surface [5]	South surface	East surface	North surface	West surface	
6	0.012	0.007	0.007	0.007	0.007	23.9	0.000	0.000	0.000	0.000	0.000	15.0
7	0.144	0.057	0.305	0.128	0.057	24.2	0.015	0.008	0.008	0.008	0.008	14.6
8	0.364	0.112	0.530	0.203	0.112	26.1	0.148	0.246	0.398	0.045	0.045	15.5
9	0.585	0.156	0.608	0.229	0.156	28.6	0.350	0.423	0.535	0.085	0.085	19.1
10	0.764	0.184	0.572	0.229	0.184	30.5	0.537	0.555	0.524	0.115	0.115	22.2
11	0.890	0.204	0.461	0.223	0.204	32.5	0.673	0.641	0.413	0.135	0.135	24.9
12	0.957	0.213	0.303	0.218	0.213	34.0	0.742	0.681	0.243	0.145	0.145	26.7
13	0.950	0.215	0.215	0.220	0.303	35.3	0.743	0.681	0.146	0.146	0.243	28.0
14	0.858	0.208	0.208	0.226	0.447	35.9	0.667	0.633	0.137	0.137	0.409	28.7
15	0.708	0.182	0.182	0.222	0.525	35.9	0.534	0.550	0.116	0.116	0.519	29.0
16	0.524	0.147	0.147	0.210	0.535	35.4	0.354	0.429	0.085	0.085	0.543	28.8
17	0.327	0.104	0.104	0.183	0.465	34.2	0.154	0.262	0.045	0.045	0.427	27.9
18	0.139	0.054	0.054	0.125	0.302	32.4	0.015	0.006	0.006	0.006	0.006	26.1
19	0.016	0.008	0.008	0.008	0.008	30.7	0.000	0.000	0.000	0.000	0.000	23.7
20	0.000	0.000	0.000	0.000	0.000	29.2	0.000	0.000	0.000	0.000	0.000	22.1
21	0.000	0.000	0.000	0.000	0.000	28.3	0.000	0.000	0.000	0.000	0.000	21.0
22	0.000	0.000	0.000	0.000	0.000	27.5	0.000	0.000	0.000	0.000	0.000	19.9
23	0.000	0.000	0.000	0.000	0.000	26.9	0.000	0.000	0.000	0.000	0.000	19.0
24	0.000	0.000	0.000	0.000	0.000	26.4	0.000	0.000	0.000	0.000	0.000	18.2
1	0.000	0.000	0.000	0.000	0.000	25.8	0.000	0.000	0.000	0.000	0.000	17.6
2	0.000	0.000	0.000	0.000	0.000	25.5	0.000	0.000	0.000	0.000	0.000	16.9
3	0.000	0.000	0.000	0.000	0.000	25.0	0.000	0.000	0.000	0.000	0.000	16.3
4	0.000	0.000	0.000	0.000	0.000	24.6	0.000	0.000	0.000	0.000	0.000	15.8
5	0.000	0.000	0.000	0.000	0.000	24.3	0.000	0.000	0.000	0.000	0.000	15.4

LAT: Local Apparent Time

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(E) Place: Srinagar (34° 05’N, 74° 50’E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^2)					Ambient temperature (^oC)**	Solar radiation (kW/m^2)					Ambient Temperature (^oC)**
	Horizontal surface*	South surface	East surface	North surface	West surface		Horizontal surface*	South surface	East surface	North surface	West surface	
6	0.064	0.034	0.034	0.034	0.034	12.3	0.0	0.0	0.0	0.0	0.0	0.5
7	0.224	0.098	0.337	0.149	0.098	12.8	0.031	0.019	0.019	0.019	0.019	0.4
8	0.413	0.153	0.497	0.178	0.153	14.0	0.108	0.160	0.224	0.058	0.058	0.4
9	0.572	0.223	0.528	0.199	0.199	15.8	0.217	0.283	0.310	0.094	0.094	0.7
10	0.697	0.304	0.499	0.233	0.233	17.0	0.308	0.375	0.314	0.117	0.117	1.8
11	0.793	0.365	0.432	0.257	0.257	18.3	0.365	0.420	0.258	0.132	0.132	2.9
12	0.831	0.393	0.328	0.269	0.269	19.5	0.386	0.430	0.180	0.138	0.138	4.0
13	0.793	0.375	0.257	0.257	0.313	20.2	0.365	0.404	0.132	0.132	0.171	4.8
14	0.697	0.324	0.233	0.233	0.381	20.9	0.308	0.341	0.117	0.117	0.215	5.4
15	0.572	0.254	0.199	0.199	0.406	21.2	0.217	0.232	0.094	0.094	0.199	5.7
16	0.413	0.169	0.153	0.153	0.369	21.2	0.108	0.094	0.058	0.058	0.100	5.5
17	0.224	0.098	0.098	0.108	0.229	21.0	0.031	0.019	0.019	0.019	0.019	5.0
18	0.064	0.034	0.034	0.040	0.064	20.5	0.0	0.0	0.0	0.0	0.0	4.2
19	0.0	0.0	0.0	0.0	0.0	19.4	0.0	0.0	0.0	0.0	0.0	3.5
20	0.0	0.0	0.0	0.0	0.0	18.0	0.0	0.0	0.0	0.0	0.0	2.8
21	0.0	0.0	0.0	0.0	0.0	16.9	0.0	0.0	0.0	0.0	0.0	2.4
22	0.0	0.0	0.0	0.0	0.0	16.1	0.0	0.0	0.0	0.0	0.0	2.0
23	0.0	0.0	0.0	0.0	0.0	15.4	0.0	0.0	0.0	0.0	0.0	1.7
24	0.0	0.0	0.0	0.0	0.0	14.9	0.0	0.0	0.0	0.0	0.0	1.5
1	0.0	0.0	0.0	0.0	0.0	14.2	0.0	0.0	0.0	0.0	0.0	1.1
2	0.0	0.0	0.0	0.0	0.0	13.8	0.0	0.0	0.0	0.0	0.0	1.1
3	0.0	0.0	0.0	0.0	0.0	13.2	0.0	0.0	0.0	0.0	0.0	0.9
4	0.0	0.0	0.0	0.0	0.0	12.9	0.0	0.0	0.0	0.0	0.0	0.7
5	0.0	0.0	0.0	0.0	0.0	12.5	0.0	0.0	0.0	0.0	0.0	0.6

LAT: Local Apparent Time

* based on procedure outlined in Mani and Rangarajan [11]

** based on procedure outlined in Bansal and Minke [12] with minimum and maximum temperature data from Mani and Rangarajan [11]

GLOBAL SOLAR RADIATION AND AMBIENT TEMPERATURE DATA

(F) Place: Leh (34^o 09'N, 77^o 34'E)

Hour (LAT)	Month: May						Month: December					
	Solar radiation (kW/m^2)					Ambient temperature (^{o}C)**	Solar radiation (kW/m^2)					Ambient Temperature (^{o}C)**
	Horizontal surface*	South surface	East surface	North surface	West surface		Horizontal surface*	South surface	East surface	North surface	West surface	
6	0.076	0.033	0.033	0.033	0.033	2.5	0.0	0.0	0.0	0.0	0.0	-12.4
7	0.266	0.096	0.520	0.185	0.096	3.1	0.036	0.017	0.017	0.017	0.017	-11.7
8	0.491	0.152	0.672	0.189	0.152	4.3	0.141	0.483	0.751	0.056	0.056	-10.3
9	0.681	0.234	0.679	0.198	0.198	6.1	0.284	0.500	0.558	0.093	0.093	-8.4
10	0.829	0.334	0.613	0.231	0.231	8.1	0.405	0.599	0.485	0.117	0.117	-6.1
11	0.943	0.409	0.504	0.256	0.256	10.3	0.480	0.649	0.359	0.133	0.133	-3.6
12	0.989	0.445	0.352	0.268	0.268	12.4	0.507	0.656	0.213	0.139	0.139	-1.2
13	0.943	0.424	0.256	0.256	0.336	14.0	0.480	0.619	0.133	0.133	0.202	0.6
14	0.829	0.363	0.231	0.231	0.444	15.1	0.405	0.535	0.117	0.117	0.300	1.8
15	0.681	0.279	0.198	0.198	0.500	15.5	0.284	0.389	0.093	0.093	0.319	2.2
16	0.491	0.176	0.152	0.152	0.478	15.1	0.141	0.208	0.056	0.056	0.230	1.8
17	0.266	0.096	0.096	0.113	0.328	14.2	0.036	0.083	0.017	0.017	0.125	0.7
18	0.076	0.033	0.033	0.051	0.119	12.7	0.0	0.0	0.0	0.0	0.0	-0.9
19	0.0	0.0	0.0	0.0	0.0	11.0	0.0	0.0	0.0	0.0	0.0	-2.9
20	0.0	0.0	0.0	0.0	0.0	9.2	0.0	0.0	0.0	0.0	0.0	-4.8
21	0.0	0.0	0.0	0.0	0.0	7.8	0.0	0.0	0.0	0.0	0.0	-6.4
22	0.0	0.0	0.0	0.0	0.0	6.5	0.0	0.0	0.0	0.0	0.0	-7.9
23	0.0	0.0	0.0	0.0	0.0	5.4	0.0	0.0	0.0	0.0	0.0	-9.1
24	0.0	0.0	0.0	0.0	0.0	4.6	0.0	0.0	0.0	0.0	0.0	-10.0
1	0.0	0.0	0.0	0.0	0.0	3.9	0.0	0.0	0.0	0.0	0.0	-10.8
2	0.0	0.0	0.0	0.0	0.0	3.3	0.0	0.0	0.0	0.0	0.0	-11.5
3	0.0	0.0	0.0	0.0	0.0	2.7	0.0	0.0	0.0	0.0	0.0	-12.1
4	0.0	0.0	0.0	0.0	0.0	2.3	0.0	0.0	0.0	0.0	0.0	-12.6
5	0.0	0.0	0.0	0.0	0.0	2.2	0.0	0.0	0.0	0.0	0.0	-12.7

LAT: Local Apparent Time

* based on procedure outlined in Mani and Rangarajan [11]

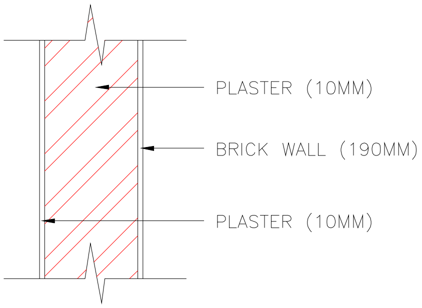
** based on procedure outlined in Bansal and Minke [12] with minimum and maximum temperature data from Mani and Rangarajan [11]

APPENDIX IV.3

EXAMPLES SHOWING ESTIMATION OF U-VALUES

Example 1:

To find U for a 19.00 cm thick brick wall provided with 1.00 cm thick cement plaster on both sides.



$L_1 = 0.01$ m; $k_1 = 0.721$ W/m-K
$L_2 = 0.19$ m; $k_2 = 0.811$ W/m-K
$L_3 = 0.01$ m; $k_3 = 0.721$ W/m-K

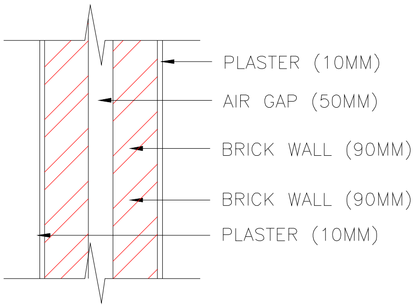
$h_i = 8.3$ W/m^2-K; $h_o = 22.7$ W/m^2-K

$R_T = 1/8.3 + 0.01/0.721 + 0.19/0.811 + 0.01/0.721 + 1/22.7 = 0.4266$

$U = 1/R_T = 1/0.4266 = 2.344$ W/m^2-K

Example 2:

To find U for an outside wall made up of two layers of 9.00 cm brick with a 5.00 cm air gap, plastered with 1.00 cm thick cement plaster on both sides.



Layer 1: $L_1 = 0.01$ m; $k_1 = 0.721$ W/m-K
Layer 2: $L_2 = 0.09$ m; $k_2 = 0.811$ W/m-K

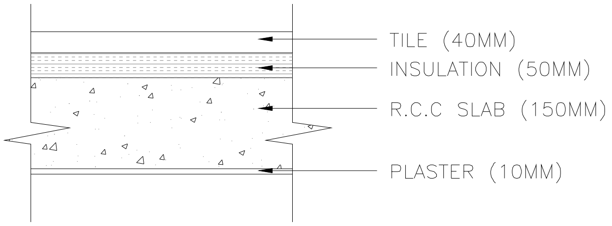
Layer 3: Enclosed air conductance $C = 6.22 \text{ W/m}^2\text{-K}$
Layer 4: $L_4 = 0.09$ m; $k_4 = 0.811$ W/m-K
Layer 5: $L_5 = 0.01$ m; $k_5 = 0.721$ W/m-K

$R_T = 1/8.3 + 1/22.7 + 0.01/0.721 + 0.09/0.811 + 1/6.22 + 0.09/0.811 + 0.01/0.721$
$= 0.5750$

$U = 1/R_T$
$= 1.739 \text{ W/m}^2\text{-K}$

Example 3:

To find U for a 15.00 cm thick RCC roof slab insulated with 5.00 cm thick expanded polystyrene, and finished with 4.00 cm thick brick tiles on the top, and 1.00 cm thick cement plaster on the bottom.



$h_i = 6.1 \text{ W/m}^2\text{-K}$; $h_o = 22.7 \text{ W/m}^2\text{-K}$

Layer 1: $L_1 = 0.01$ m; $k_1 = 0.721$ W/m-K
Layer 2: $L_2 = 0.15$ m; $k_2 = 1.580$ W/m-K
Layer 3: $L_3 = 0.05$ m; $k_3 = 0.035$ W/m-K
Layer 4: $L_4 = 0.04$ m; $k_4 = 0.798$ W/m-K

$R_T = 1/6.1 + 1/22.7 + 0.01/0.721 + 0.15/1.580 + 0.05/0.035 + 0.04/0.798$
$= 1.795$

$U = 1/R_T$
$= 0.55 \text{ W/m}^2\text{-K}$

APPENDIX IV.4

AVERAGE EMISSIVITIES, ABSORPTIVITIES AND REFLECTIVITIES OF SOME BUILDING MATERIALS [4]

Surface	Emmisivity or Absorptivity		Reflectivity (Solar radiation)
	(Low temperature radiation)	(Solar radiation)	
Aluminium, bright	0.05	0.20	0.80
Asbestos cement, new	0.95	0.60	0.40
Asbestos cement, aged	0.95	0.75	0.25
Asphalt pavement	0.95	0.90	0.10
Brass and copper, dull	0.20	0.60	0.40
Brass and copper, polished	0.02	0.30	0.70
Brick, light puff	0.90	0.60	0.40
Brick, red rough	0.90	0.70	0.30
Cement, white portland	0.90	0.40	0.60
Concrete, uncoloured	0.90	0.65	0.35
Marble, white	0.95	0.45	0.55
Paint, Aluminium	0.55	0.50	0.50
Paint, white	0.90	0.30	0.70
Paint, brown, red, green	0.90	0.70	0.30
Paint, black	0.90	0.90	0.10
Paper, white	0.90	0.30	0.70
Slate, dark	0.90	0.90	0.10
Steel, galvanized new	0.25	0.55	0.45
Steel, galvanized weathered	0.25	0.70	0.30
Tiles, red clay	0.90	0.70	0.30
Tiles, uncoloured concrete	0.90	0.65	0.35

APPENDIX IV.5

SIMULATION TOOLS

A brief description of a few simulation tools is presented in this appendix.

1 Therm Version 1.0 (Thermal Evaluation Tool for Buildings) [13]

"Therm" evaluates the thermal performance of a passive or partly air-conditioned building, by calculating the hourly floating inside air temperature. The tool considers the effects of various parameters and variables like building fabric, opening/fenestration type, orientation, natural ventilation, and internal gains through convection and radiation. Effects of passive elements such as Trombe wall, evaporative cooling and roof pond can be analysed using Therm. It is intended as a preliminary tool for the analysis of thermal performance of a building, to help select a suitable building envelope or passive system appropriate for a particular climate and function. Therm incorporates various rating criteria such as comfort fraction, decrement factor, and depression or elevation of mean indoor temperature. The tool is developed using Microsoft Excel and Visual basic and is in a spread sheet format. It is used as a plug-in in MS Excel.

Therm has a facility to update the materials library and the climatic database. A handy tool for calculating the U-value of various building sections is also provided.

2. TADSIM (Tools for Architectural Design and Simulation) [14]

TADSIM has been developed as a computer interface between building design and simulation software. The basic philosophy is to ensure that architects can make use of simulation tools quickly and efficiently. Relevant information on building geometry and associated details are automatically extracted from the design made in the architectural design module (TAD Designer). This information can be passed on to a number of simulation tools namely Dynsim, TRNSYS and DOE2.1E for thermal analysis. Dynsim has been integrated into TADSIM for dynamic simulation of non-conditioned and conditioned multi-storey, multi-zone buildings. It estimates the room temperatures and thermal loads. This tool can be used to quickly analyse the effect of materials, windows, orientation, colour, etc. on the thermal performance of the building. The effect of shading of external surfaces can be approximated by specifying a shade fraction for each window.

TADSIM is also capable of generating input files for TRNSYS and DOE2.1E, if the user wants to use these for simulating the building's thermal performance. Besides, it has a module that advises the user on various aspects of passive solar architecture, called TADSIM adviser. It provides information on climatic design, daylighting, passive solar techniques and material properties. It also contains a glossary. Additionally the data can be updated by the user at a later stage.

3. TRNSYS

TRNSYS is a dynamic simulation tool for estimating the performance of any solar thermal system. For example, it can estimate the performance of a building, a solar photovoltaic system, and solar domestic hot water system. It is one of the most widely used commercially available tool for building simulation. It uses a menu driven interface to provide the building description (building geometry, materials and their properties, scheduling, heating and cooling system, etc.) using the PREBID module. This file can also be edited directly using any text editor (e.g. Notepad, MS Editor), without using PREBID, if one knows the sequence of information needed for the software.

The weather data, simulation run time, output types can be provided by using the IISiBat or PRESIM interface, or manually edited using any text editor. TRNSYS can be used with a general purpose CAD software called SimCAD, to integrate the architectural design and simulation.

The output of a building's thermal performance in terms of temperature and loads, can be obtained both graphically and in text format. Multi-zone, conditioned and non-conditioned buildings can be analysed by using TRNSYS. It can also do quick parametric analyses by using parameter tables. It has a built-in materials library.

4. DOE-2.1E [6]

DOE-2.1E predicts the hourly energy use and energy cost of a building. The inputs required are hourly weather information, building geometric dimensions, and its HVAC description. Designers can determine the choice of building parameters that improve energy efficiency, while maintaining thermal comfort and cost-effectiveness. DOE-2.1E has one subprogram for translation of input (BDL Processor),and four simulation subprograms (LOADS, SYSTEMS, PLANT and ECONOMICS). LOADS, SYSTEMS, PLANT and ECONOMICS are executed in sequence, with the output of LOADS becoming the input of SYSTEMS, and so on. Each of the simulation subprograms also produces printed reports of the results of its calculations. The Building Description Language (BDL) processor reads input data and calculates response factors for the transient heat flow in walls, and weighting factors for the thermal response of building spaces.

The LOADS simulation subprogram calculates the sensible and latent components of the hourly heating or cooling load for each constant temperature space, taking into account weather and building use patterns. The SYSTEMS subprogram calculates the performance of air-side equipment (fans, coils, and ducts); it corrects the constant-temperature loads calculated by the LOADS subprogram by taking into account outside air requirements, hours of equipment operation, equipment control strategies, and thermostat set points. The output of SYSTEMS is air flow and coil loads. PLANTS calculates the behavior of boilers, chillers, cooling towers, storage tanks, etc., in satisfying the secondary systems heating and cooling coil loads. It takes into account the part-load characteristics of the primary equipment, to calculate the fuel and electrical demands of the building. The ECONOMICS subprogram calculates the cost of energy and so, can be used to compare the cost benefits of different building designs, or to calculate savings for retrofits to an existing building.

A number of interfaces have been developed to make the program easy to use.

5. EnergyPlus [16]

EnergyPlus is a modular, structured software tool based on the most popular features and capabilities of BLAST and DOE-2.1E. It is primarily a simulation engine; input and output are simple text files. EnergyPlus grew out of a perceived need to provide an integrated (simultaneous load and systems) simulation for accurate temperature and comfort prediction. Loads calculated (by a heat balance engine) at user-specified time step (15-minute default) are passed to the building system simulation module at the same time step. The EnergyPlus building systems simulation module, with a variable time step (down to 1 minute as needed), calculates the heating and cooling system, and plant and electrical system response. This integrated solution provides more accurate space-temperature prediction, crucial for system and plant sizing, and occupant comfort and health calculations. Integrated simulation also allows users to evaluate realistic system controls, moisture adsorption and desorption in building elements, radiant heating and cooling systems, and interzone air flow.

EnergyPlus has two basic components: a heat and mass balance simulation module, and a building systems simulation module. The heat and mass balance calculations are based on IBLAST – a research version of BLAST with integrated HVAC systems and building loads simulation. The heat balance module manages the surface and air heat balance, and acts as an interface between the heat balance and the building system simulation manager. EnergyPlus inherits three popular windows and daylighting models from DOE-2.1E – fenestration performance based on WINDOW 5 calculations, daylighting using the split-flux interreflection module, and antistrophic sky models. In addition, a new daylighting analysis module named 'Delight' has been integrated with EnergyPlus.

6. eQUEST [17]

eQUEST is an easy to use building energy use analysis tool that provides professional-level results with an affordable level of effort. This is accomplished by combining a building creation wizard, an energy efficiency measure (EEM) wizard and a graphical results display module, with an enhanced DOE-2.2-derived building energy use simulation program.

eQUEST features a building creation wizard that guides the user through the process of creating an effective building energy model. This involves following a series of steps that help one to describe the features of the design that would impact energy use such as architectural design, HVAC equipment, building type and size, floor plan layout, construction material, area usage and occupancy, and lightning system. After compiling a building description, eQUEST produces a detailed simulation of the building, as well as an estimate of how much energy the building would use.

Within eQUEST, DOE-2.2 performs an hourly simulation of the building design for a one-year period. It calculates heating or cooling loads for each hour of the year, based on factors such as walls, windows, glass, people, plug loads, and ventilation. DOE-2.2 also simulates the performance of fans, pumps, chillers, boilers, and other energy-consuming devices. During the simulation, DOE-2.2 tabulates the building's projected use for various end uses.

eQUEST offers several graphical formats for viewing simulation results. It allows one to perform multiple simulations and view alternative results in side-by-side graphics. It offers features like: energy cost estimating, daylighting and lighting system control , and automatic implementation of common energy efficiency measures (by selecting preferred measures from a list).