Chapter Five
Thermal Design

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1. Introduction

Thermal design of buildings for thermal comfort requires a knowledge of thermal quantities involved in heat flow, especially as a preliminary to understanding the basic thermal properties of building materials and elements: air-to-air transmittance, solar gain factor, time lag and admittance. Thermal balance of buildings requires that heat flow be equal to heat gain. Periodic heat flow calculations assume non-steady state conditions as opposed to steady state conditions. The required thermal performance of walls and roofs are established by codes for different climatic zones - hot dry climates, warm humid climates, cold climates and composite climates. The design of floors in the various climates requires special attention both for moderation of indoor temperatures and foot comfort. The problem of surface and interstitial condensation can be solved by good thermal design.

2. Thermal Quantities

There are several thermal quantities used in discussions about heat flow through buildings. An understanding of these quantities and their units of measurement is necessary for thermal design which aims at utilizing thermal properties of building elements to achieve and maintain comfort in buildings.

Temperature:
This is an indication of the thermal state of a body and it is measured in degrees Celsius (C) or degrees Kelvin (K).

Heat:
This is a form of energy measured in Joules (J).

Specific heat:
Specific heat of a substance is the amount of heat energy necessary to cause unit temperature increase of a unit mass of the substance. It is measured in J/kg deg C.

Thermal Capacity:
Thermal capacity of a body is the amount of heat required to raise the temperature of the body by one unit. It is measured in J/deg C.

Power:
This is the ability to carry out a certain work in unit time -measured in Watts (W), that is J/S.

Thermal conductivity
Thermal conductivity of a material is the rate of heat flow through a unit area of unit thickness of the material for a unit temperature difference across the material. It is also known as the K-value and is measured in W/m deg C. Good insulators have lower thermal conductivities.

Thermal Conductance:
This is the rate of heat flow through a unit area of a body when the temperature difference between the two surfaces is one degree Celsius. It is measured in W/m^2 deg C.

Thermal resistivity:
This is the reciprocal of thermal conductivity. It is measured in m deg C/W. Good insulators have high thermal resistivities.

Thermal resistance
Thermal resistance: is the reciprocal of thermal conductance.

Surface resistance and conductance:
Surface resistance refers to the resistance offered to heat flow by the surface of a body, as different from the resistance offered by the body itself. The surface conductance is the reciprocal of surface resistance. The units are the same as for thermal resistance and conductance.

Air-to-air resistance
Air-to-air resistance is the sum of the resistance of the body and the internal and external surface resistances.

$$R_a = R_{si} + R_b + R_{so}$$

Where:

R_a = air-to-air resistance.
R_{si} = internal surface resistance.
R_b = body resistance.
R_{so} = external surface resistance.
The unit of measurement is the same as for resistance.

Cavity resistance and conductance:
Cavity resistance is the resistance offered to heat flow by a cavity enclosed within a body. The reciprocal is cavity conductance.

Absorptivity:
This is the property of a surface which determines what proportion of incident radiation it absorbs.

Sol-air temperature:
Combines the heating effect of radiation incident on a building with the effect of warm air. It is measured in degrees Celsius.

$$T_s = T_o + (I \times a)/ F_o$$

Where:

T_s = sol-air temperature.
T_o = outside air temperature.
I = radiation intensity.
a = absorbance of the surface.
F_o = outside surface conductance

.3. Thermal Properties of Building Materials and Elements

Heat transmission and absorption by building materials is affected by the absorptivity, the conductivity and thermal capacity of the materials. These properties of materials determine the characteristics of wall and roof elements and therefore the way they will modify the thermal environment.

Building elements possess four characteristics which affect the internal conditions -the air-to-air transmittance (U-value), the solar gain factor, the time lag and the admittance.

Air-To-Air Transmittance:
This is the reciprocal of air-to-air resistance. It is commonly known as U-value and measured in the same unit as conductance. It is defined as the rate at which heat is transmitted from the air on one side of a wall or roof to the air on the other side.

Solar Gain Factor:
This is the rate of heat flow through a construction due to solar radiation expressed as a fraction of the incident solar radiation.

Time Lag:
This is the time delay between the impact of the diurnal variation of temperature and radiation on the external surface, and the resultant temperature variation on the internal surface. See figure 1.

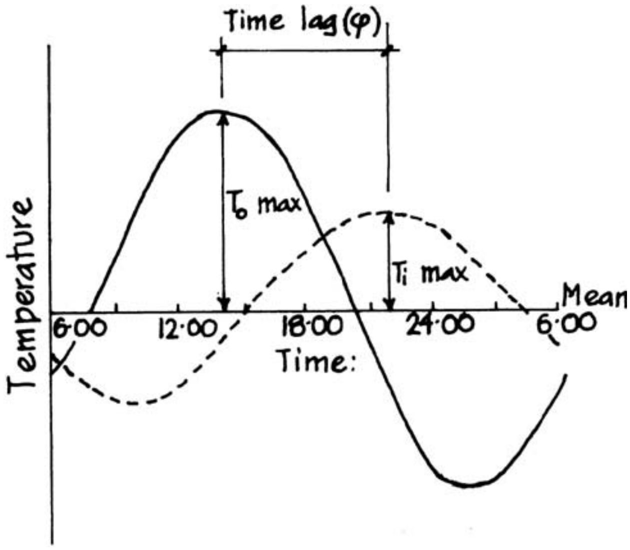
Admittance:
Admittance of a surface is the rate at which the surface absorbs or emits heat from or to the air when the air temperature is different from the temperature of the surface.

4. Heat Flow through Buildings

The total heat gained by a building must be lost in order to maintain a thermal balance. An excess heat gain will result in a constant rise in temperature of the building while an excess heat loss will cause a fall in temperature.

Heat Gains:
Buildings gain heat by conduction through the walls, by insolation through windows, internally from occupants and appliances, by natural ventilation and from heating equipment.

Heat Losses:
Buildings lose heat by conduction, evaporation, natural ventilation and through mechanical cooling aids.



$$\text{Decrement factor} : \mu = \frac{T_i\ max}{T_o\ max}$$

Figure 1: Time lag and decrement factor.

In a state of equilibrium therefore, the heat loss is equal to the heat gain. See figure 2. We can calculate one of these loads given the others from the equation below.

$$Q_i + Q_s + Q_c + Q_v + Q_m + Q_e$$

Where:

- Q_i = internal heat gain rate (W).
- Q_s = solar heat gain rate (W).
- Q_c = rate of heat loss or heat gain by conduction (W).
- Q_v = rate of heat loss or heat gain by ventilation (W).
- Q_m = mechanical heat gain or loss rate (W).
- Q_e = rate of heat loss by evaporation (W).

We can calculate, for example, the amount of mechanical cooling or heating required in an existing or freshly designed building. We may also find out how much insolation is needed to heat a solar house with no auxiliary heating from this equation. In heat gain or heat loss calculations the various sources of loading are considered individually.

Conduction:

This is usually calculated for walls of a given area and is the product of the surface area, the transmittance value and the temperature difference between the exterior and the interior. See the equation below.

$$Q_c = A \times U \times \quad T$$

Where:

- Q_c = rate of heat loss or heat gain by conduction (W).
- A = surface area (m^2).
- U = transmitance value (W/m^2 degC).
- T = temperature difference.

Convection:

This refers to heat loss or heat gain through the exchange of air between the building and the open air and it covers infiltration as well as natural and forced ventilation. The rate of ventilation heat flow is the product of the volumetric specific heat of air, the ventilation rate and the temperature difference. See the equation below.

$$Q_v = 1300 \times U \times \quad T$$

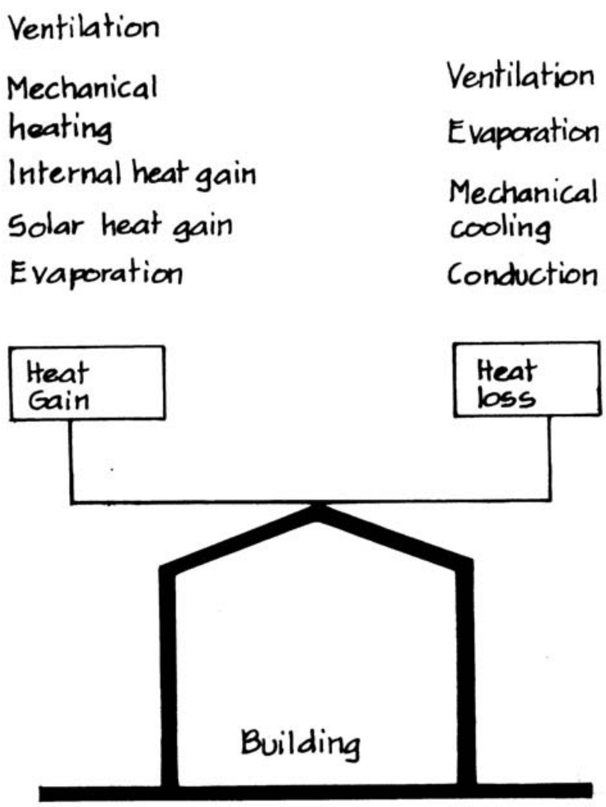


Figure 2: Thermal balance of buildings.

Where:

Q_v = rate of heat loss or heat gain by ventilation (W).
U = transmitance value (W/m^2 degC).
T = temperature difference.

Solar Gains:

The glass in windows acts as a filter and its type and quality reduces the solar heat gain by the solar gain factor. The actual solar gain will then be a product of the area of the window, the intensity of solar radiation and the solar gain factor. See the equation below.

$$Q_s = A \times I \times$$

Where:

Q_s = solar heat gain rate (W).
A = surface area (m^2).
I = radiation heat flow density (W/m^2).
= solar gain factor of window glass.

The Greenhouse Effect:

Short-wave radiation incident on glass is partly reflected, partly absorbed but mainly transmitted. This is because glass is "transparent" to short-wave radiation. Other materials, such as concrete or mud however absorb the larger portion of short-wave radiation. The absorbed energy causes a rise in their temperature and this energy is emitted in the form of long-wave radiation. Glass is "opaque" to long-wave radiation and if it encloses the emitter the heat is trapped within the enclosure. This leads to a rise in temperature within the enclosure known as the greenhouse effect. See figure 4.

Internal Heat Gains:

The internal heat gains are made up of the heat output of the occupants, and the lamps and motors, if any, in the enclosure. The human body produces about 70 W while sleeping and a maximum of about 1100 W. Sedentary activity produces about 140 W. The lamps and motors usually have their wattage marked. The total internal heat gain is the sum of heat production by the individual persons or equipment. See the equation below.

$$Q_i = n_1 x q_1 + n_2 x q_2 + \ldots.. n_n x q$$

Where:

Q_i = internal heat gain rate (W).

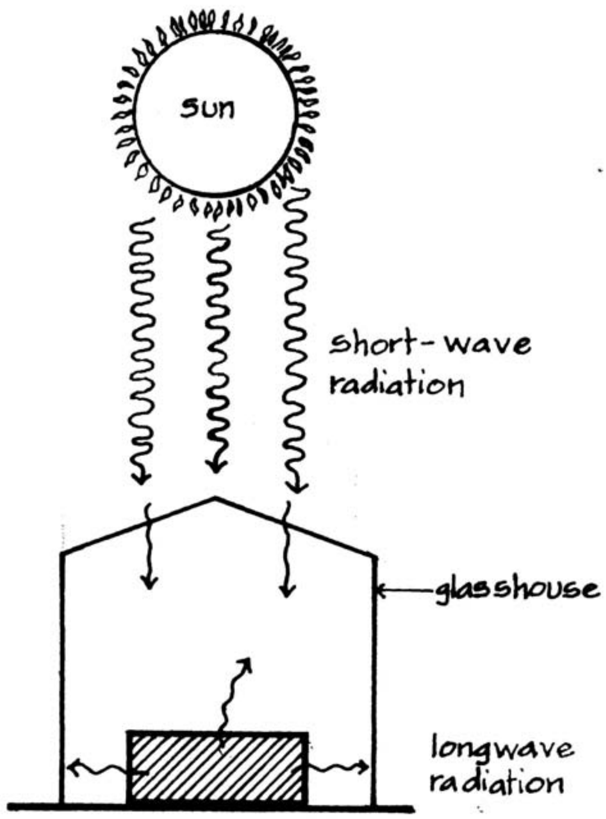


Figure 4: The greenhouse effect. The shortwave radiation is transmitted by the glass, absorbed by the concrete mass and emitted as longwave radiation.

$N_1 x q_1$ = number of persons or equipment.
$n_2 x q_2$ = heat output rate of persons or equipment.

Mechanical Devices:
These are usually heaters or air-conditioners and their rating is usually indicated.

Evaporation:
This refers to heat loss from the interior or exterior of the building by evaporation, for example from roof ponds or fountains. It is usually ignored except for detailed studies of air-conditioning.

5. Periodic Heat Flow

Simple calculations of the thermal balance of a building assume that both the indoor and outdoor temperatures are constant. This assumption of steady state conditions are unreliable when there are large fluctuations in temperatures. In such a case, non-steady state conditions are assumed.

In climates with large diurnal temperature ranges the variations in temperature are clearly marked. There is a 24-hour cycle of increasing and decreasing temperatures with the minimum temperature around 6.00 am and the maximum around 2.00 pm. The fabric of the building absorbs and stores some of the heat during the day and releases this heat to the interior during the night. The variation of temperatures inside the building also has a fixed cycle but the peak occurs at a different time depending on the time lag. The cycle is further characterised by the decrement factor which is the ratio of the maximum outer and inner surface temperature amplitudes taken from the mean. See figure 1.

Periodic Heat Flow Calculation
Knowledge of the time lag and decrement factor for different materials can be used to design buildings capable of reducing heat flow into buildings during the hot afternoons and using the stored energy to heat the building during the cold nights. Such a building will be very useful during the cold harmattan but may prove uninhabitable during the hot season. It is necessary to make calculations of the periodic heat flow through the building for different seasons of the year to obtain the optimal time lag

and decrement factor. The momentary heat flow rate is calculated using the equation below.

$$Q = A \times U \times [(T_m - T_i) + \quad (T \quad - T_m)]$$

Where:

Q =	momentary heat flow rate (W).
A =	area of wall or roof (m^2).
U =	transmittance (W/m^2degC).
T_m =	daily mean outdoor sol-air temperature (C).
T_i =	constant indoor temperature (C).
T =	outdoor sol-air temperature hours earlier(C).
=	decrement factor.
=	time lag.

6. Required Thermal Performance of Building Elements

The required thermal performance of walls and roofs are established by codes for different climatic zones. The aim of this is to reduce heating costs and reduce the discomfort of occupants in case of inadequate heating. These recommendations are based on economic analysis involving the cost of heating and the cost of building materials. The optimal values vary from country to country and are influenced by the climate and living standards.

In Nigeria heating is required only for a few weeks during the harmattan, especially in the northern parts of the country where the harmattan can be very severe. In practice, heating appliances are very rarely installed and people resort to other means of keeping warm. Peasants sometimes keep a fire burning in their rooms and block all apertures to reduce infiltration. The design of walls and roofs in this climate should ensure adequate insulation and thermal capacity.

The major problem in Nigeria is however that of overheating. In the warm humid climates found near the coast, conditions are uncomfortably hot during most of the year. In these conditions thermal storage should be avoided and high insulation provided. The choice of either air-conditioning or fans will influence the size and type of windows used. We shall now consider four climates and the performance of walls and roofs required for them. See Table 1.

Hot Dry Climates:

These climates are characterised by a high diurnal temperature range and low humidity with discomfort caused by either high or low temperatures. The design of walls and roofs should therefore moderate temperature fluctuations. This is achieved by a long time lag of 8 to 14 hours for both internal and external walls. See figure 5.

Warm Humid Climates

These climates are characterised by a low diurnal temperature range, high humidity and generally high temperatures. Comfort is achieved by

Table 1: Recommended thermal properties for walls and roofs.

Climate	Element	Condition	Max "U" value	Time lag
Hot dry	Roofs	Rooms for night use: diurnal range 10 C	0.90	8 - 14
		Rooms for night use: diurnal range 12.5 C	0.85	8 - 14
		Rooms for night use: diurnal range 15 C	0.80	8 - 14
		Rooms for night use: diurnal range 17.5 C	0.75	8 - 14
		Rooms for night use: diurnal range 20 C	0.70	8 - 14
		Rooms for day use only	-	8 - 14
		Schools and offices	-	4 - 7
	Heavy walls	East wall	1.2	10 - 16
		West wall	1.2	6 - 14
		North and south walls	1.2	8 - 14
		Walls shaded from direct solar radiation	2.0	8 - 14
Warm humid	Roof	Rooms for day and night use	1.1	0 - 3
		Rooms for day use only	1.1	0 - 14
	Walls	West wall	2.0	0 - 5
		East, south and north walls	2.0	0 - 5
		Walls shaded from direct solar radiation	2.8	0 - 14
Composite	Light roofs	Rooms for day and night use	0.85	0 - 4
		Rooms for day use only	0.85	0 - 14
	Walls	West walls	1.2	0 - 5
		East, north and south walls	1.5	0 - 5
		Walls shaded from direct solar radiation	2.0	0 - 14

ventilation and by restricting the flow of heat into the building. To achieve this a short time lag, low thermal capacity, high insulation and reflective roofs are used. See figure 6.

Cold Climates

Cold climates are distinguished by low air temperatures. The design of walls and roofs should therefore prevent loss of heat. An additional problem is condensation which can form on internal surfaces if temperatures are allowed to drop too low. The preservation of heat is achieved through high insulation and auxiliary heating in severe cases. The insulation provided must prevent condensation on the internal surfaces.

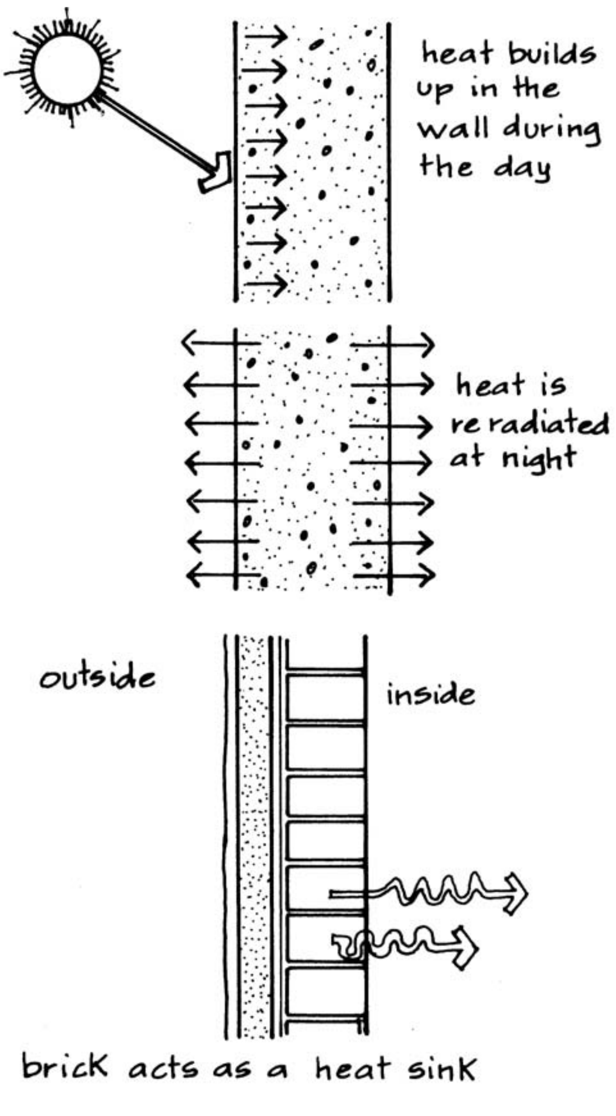


Figure 5: Wall treatment - thermal capacity.

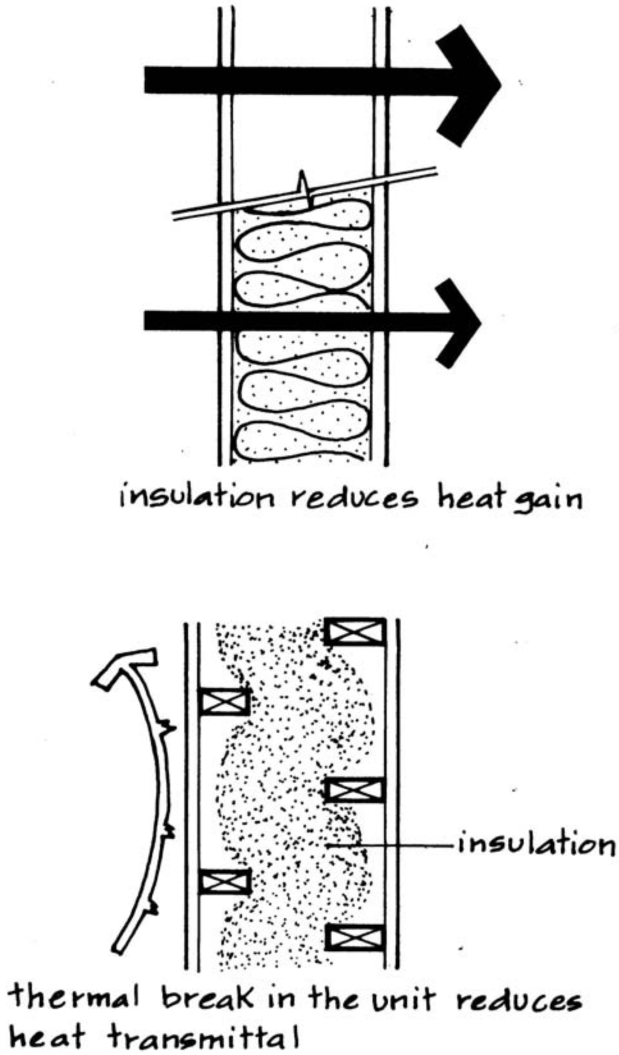


Figure 6: Wall treatment - insulation.

Composite Climates

Composite climates are characterised by alternating hot dry, cold dry and warm humid seasons. The design of roofs and walls depends on the relative duration of the seasons. Light, insulated walls and roofs are used when the dry season is up to two months while heavy walls and light roofs are used when the dry season lasts for more than three months.

Floors

Floors also influence the thermal environment within buildings and their design should be considered along with that of walls and roofs. In hot dry climates the floor should help moderate temperatures. This is achieved by heavy floors laid in direct contact with the ground thereby utilizing the high thermal capacity of the soil. In severe cases buildings should be partly or totally submerged. In warm humid climates the floor should help in cooling down the building at night. Light floors raised well above the ground improve the cooling rate but where this is not architecturally feasible a heavy floor in direct contact with the ground is used.

In cold climates floors should be well insulated to prevent heat loss and probable condensation. In composite climates heavy floors are used.

Foot comfort is very important in the design of floors. The thermal sensation experienced by the bare foot on a floor is however dependent not on the subfloor but on the finish. The choice of finishes should therefore depend on the climate and the average air temperature in dwellings. In hot climates PVC tiles or terrazzo may be adequate while softwood or carpets may be needed in colder climates. See Table 2.

Table 2: Comfortable floor temperatures.

Material	Comfortable floor temperature for bare feet C
Iron/steel	29.5
Gravel concrete	25.5 to 26.5
Granolithic	26
Terrazzo tiles	26
Quarry tiles	25
Foam slag concrete	24
Brick	24 to 25
Linoleum	22
Rubber floor tiles	22
Hard wood	21 to 22
P.V.C. tiles	22
Plaster	19
Softwood	17 to 19
Cork floor tiles	15 to 16
Insulation board	below 5
Carpet	below 5
Cork	below 5

7. Condensation

The amount of vapour air can hold depends on the air temperature. Warm air can hold more vapour than air at a lower temperature as is illustrated in table 3. When warm air is cooled therefore, there comes a time when the vapour in the air is sufficient to saturate the air mass. The vapour pressure at this temperature is called the saturation vapour pressure while the temperature is the dew point of air for the given vapour content. When the air is cooled further, it will no longer be able to hold some of the vapour and this excess vapour is converted to a liquid in a process called condensation.

There are two types of condensation - surface and interstitial condensation. **Surface condensation** occurs when air comes into contact with a surface at a temperature below its dew point. A layer of moisture is formed on the surface of the wall or roof as may be observed in some kitchens, bathrooms or rooms. This leads to damp interiors and mould growth.

Interstitial condensation is condensation within walls or roofs. This is a result of temperature and vapour pressure gradients across the wall. It may also be caused by surface condensation being absorbed into the wall. This may cause damage to organic building materials and increase heat loss through a reduction in resistance of the building material.

The factors affecting condensation are the indoor vapour pressure level, the temperature and absorptivity of the internal surfaces and the vapour transmission of walls. Interstitial condensation is prevented by predicting dew point temperatures at different points within the wall and checking if these do not cause condensation. Adequate insulation should be provided and cold bridges avoided. It is sometimes necessary to restrict vapours to bathrooms, washing rooms and kitchens. Good ventilation will reduce the risk of surface condensation.

Table 3: Saturation vapour pressure as a function of air temperature.

Saturation vapour pressure				
Air temp. C	KN/m^2	mmHg	g/m^3	g/kg of dry air
0	0.61	4.6	4.8	3.8
5	0.87	6.5	6.8	5.4
10	1.23	9.2	9.4	7.6
15	1.71	12.8	12.8	10.5
20	2.33	17.5	17.3	14.4
25	3.17	23.8	23.0	19.4
30	4.23	31.7	30.4	26.2
35	5.60	42.0	39.6	34.7

8. Tests and Exercises

1. Describe how a building maintains its thermal balance.

2. With the aid of sketches, analyze how heat is gained by buildings.

3. List ten thermal quantities used in discussions on heat flow through buildings.

4. What are the effects of the environment on the following building materials:

   a. Steel

   b. Concrete

   c. Timber

d. Plastic

5 What is meant by thermal conductivity of a material?

6. Materials like coke, slag wool and glass wool are known for their excellent insulating qualities. Explain why?

7. What happens to materials like coke, slag wool and glass wool when they become wet? Explain.

8. Discuss the various ways dampness gets into the interior of a building. How can you prevent this as a designer?

9. Differentiate between surface and interstitial condensation explaining methods of their prevention in buildings.

10. List four characteristics of building elements which affect the interior comfort conditions.

11. Describe the greenhouse effect.

12. Briefly define the following:

(a). Non-steady state conditions

(b). Foot comfort

(c). Dew point

(d). interstitial condensation.

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