Lesson 29

Inside And Outside Design Conditions

The specific objectives of this lecture are to:

1. Describe a typical air conditioning system and discuss the need for fixing suitable indoor and outdoor design conditions (*Section 29.1*)
2. Discuss the criteria used for selecting inside design conditions (*Section 29.2*)
3. Define thermal comfort, metabolic rate and response of human beings to variation in body temperature (*Section 29.3*)
4. Present heat balance equation, equations for convective, radiative and evaporative losses from the skin, metabolic rates for various types of activities and discuss the thermo-regulatory mechanism used by human body to fight against heat and cold (*Section 29.4*)
5. Discuss the factors affecting thermal comfort (*Section 29.5*)
6. Discuss the various thermal indices used for evaluating indoor environment and present ASHRAE comfort chart, recommended inside design conditions and discuss the concept of Predicted Mean Vote (PMV) and Percent of People Dissatisfied (PPD) (*Section 29.6*)
7. Discuss the criteria used for selecting outside design conditions and present typical summer design conditions for major Indian cities as suggested by ASHRAE (*Section 29.7*)

At the end of the lecture, the student should be able to:

1. Explain the need for selecting design inside and outside conditions with respect to a typical air conditioning system
2. Define thermal comfort, metabolism, metabolic rate and discuss the effects of variation in body temperatures on human beings
3. Write the heat balance and heat transfer equations from a human body and using these equations, estimate various heat transfer rates
4. List the factors affecting thermal comfort
5. Define the various thermal indices used in evaluating indoor environment
6. Draw the ASHRAE comfort chart and mark the comfort zones for summer and winter conditions
7. Select suitable indoor design conditions based on comfort criteria
8. Define PMV and PPD and explain their significance
9. Explain the method followed for selecting suitable outside design conditions

29.1. Introduction:

Design and analysis of air conditioning systems involves selection of suitable inside and outside design conditions, estimation of the required capacity of cooling or heating equipment, selection of suitable cooling/heating system, selecting supply conditions, design of air transmission and distribution systems etc. Generally, the inputs are the building specifications and its usage pattern and any other special requirements. Figure 29.1 shows the schematic of a basic summer air conditioning system. As shown in the figure, under a typical summer condition, the building gains sensible and latent heats from the surroundings and also due to internal heat sources (RSH and RLH). The supply air to the building extracts the building heat gains from the conditioned space. These heat gains along with other heat gains due to ventilation, return ducts etc. have to be extracted from the air stream by the cooling coil, so that air at required cold and dry condition can be supplied to the building to complete the cycle. In general, the sensible and latent heat transfer rates (GSH and GLH) on the cooling coil are larger than the building heat gains due to the need for ventilation and return duct losses. To estimate the required cooling capacity of the cooling coil (GTH), it is essential to estimate the building and other heat gains. The building heat gains depend on the type of the building, outside conditions and the required inside conditions. Hence selection of suitable inside and outside design conditions is an important step in the design and analysis of air conditioning systems.

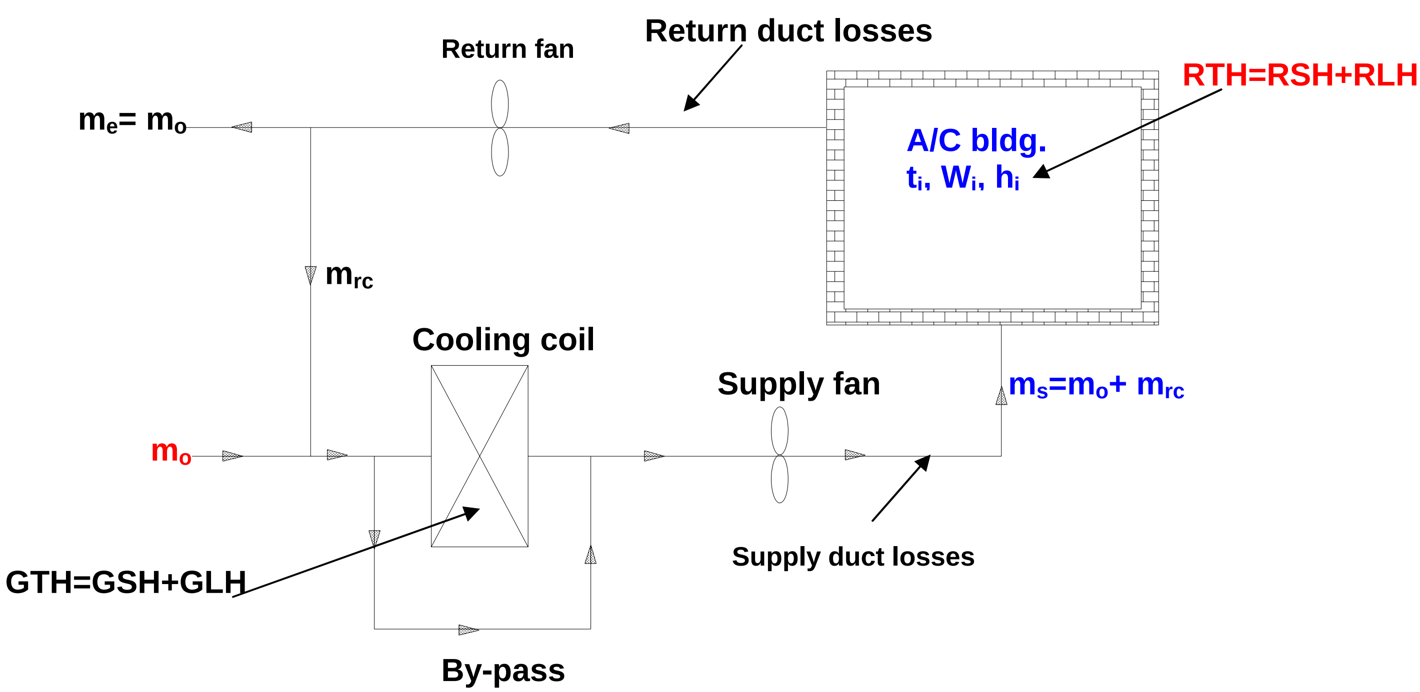

Fig.29.1: *Schematic of a basic summer air conditioning system*

29.2. Selection of inside design conditions:

The required inside design conditions depend on the intended use of the building. Air conditioning is required either for providing suitable comfort conditions for the occupants (e.g. comfort air conditioning), or for providing suitable conditions for storage of perishable products (e.g. in cold storages) or conditions for a process to take place or for products to be manufactured (e.g. industrial air conditioning). The required inside conditions for cold storage and industrial air conditioning applications vary widely depending on the specific requirement. However, the required inside conditions for comfort air conditioning systems remain practically same irrespective of the size, type, location, use of the air conditioning building etc., as this is related to the thermal comfort of the human beings.

29.3. Thermal comfort:

Thermal comfort is defined as "that condition of mind which expresses satisfaction with the thermal environment". This condition is also some times called as "neutral condition", though in a strict sense, they are not necessarily same. A living human body may be likened to a heat engine in which the chemical energy contained in the food it consumes is continuously converted into work and heat. The process of conversion of chemical energy contained in food into heat and work is called as "metabolism". The rate at which the chemical energy is converted into heat and work is called as "metabolic rate". Knowledge of metabolic rate of the occupants is required as this forms a part of the cooling load of the air conditioned building. Similar to a heat engine, one can define thermal efficiency of a human being as the ratio of useful work output to the energy input. The thermal efficiency of a human being can vary from 0% to as high as 15-20% for a short duration. By the manner in which the work is defined, for most of the light activities the useful work output of human beings is zero, indicating a thermal efficiency of 0%. Irrespective of the work output, a human body continuously generates heat at a rate varying from about 100 W (e.g. for a sedentary person) to as high as 2000 W (e.g. a person doing strenuous exercise). Continuous heat generation is essential, as the temperature of the human body has to be maintained within a narrow range of temperature, irrespective of the external surroundings.

A human body is very sensitive to temperature. The body temperature must be maintained within a narrow range to avoid discomfort, and within a somewhat wider range, to avoid danger from heat or cold stress. Studies show that at neutral condition, the temperatures should be:

Skin temperature, $t_{skin} \approx \mathbf{33.7^oC}$

Core temperature, $t_{core} \approx \mathbf{36.8^oC}$

At other temperatures, the body will feel discomfort or it may even become lethal. It is observed that when the core temperature is between 35 to 39^oC, the body experiences only a mild discomfort. When the temperature is lower than 35^oC or higher than 39^oC, then people suffer major loss in efficiency. It becomes lethal when the temperature falls below 31^oC or rises above 43^oC. This is shown in Fig. 29.2.

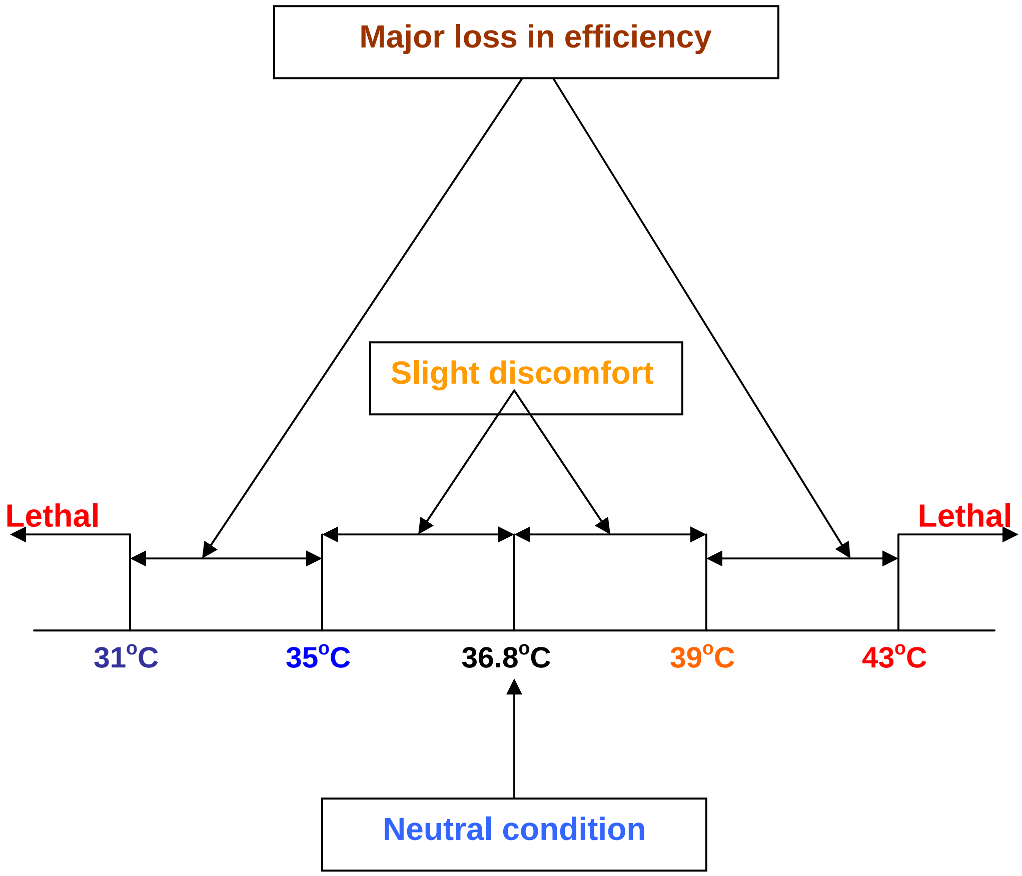

***Fig.29.2**: Affect of the variation of core temperature on a human being*

29.4: Heat balance equation for a human being:

The temperature of human body depends upon the energy balance between itself and the surrounding thermal environment. Taking the human body as the control volume, one can write the thermal energy (heat) balance equation for the human body as:

$$\mathbf{Q_{gen} = Q_{sk} + Q_{res} + Q_{st}} \qquad (29.1)$$

where Q_{gen} = Rate at which heat is generated inside the body

Q_{sk} = Total heat transfer rate from the skin

Q_{res} = Heat transfer rate due to respiration, and
Q_{st} = Rate at which heat is stored inside the body

The heat generation rate Q_{gen} is given by:

$$\mathbf{Q_{gen} = M(1-\eta) \approx M} \tag{29.2}$$

where M = Metabolic rate, and
η = Thermal efficiency $\approx$ 0 for most of the activities

The metabolic rate depends on the activity. It is normally measured in the unit "**met**". A met is defined as the metabolic rate per unit area of a sedentary person and is found to be equal to about **58.2 W/m^2**. This is also known as "basal metabolic rate". Table 29.1 shows typical metabolic rates for different activities:

Typical metabolic rates

Activity	Specifications	Metabolic rate
Resting	**Sleeping**	**0.7 met**
	Reclining	**0.8 met**
	Seated, quite	**1.0 met**
	Standing, relaxed	**1.2 met**
Walking	**0.89 m/s**	**2.0 met**
	1.79 m/s	**3.8 met**
Office activity	**Typing**	**1.1 met**
Driving	**Car**	**1.0 to 2.0 met**
	Heavy vehicles	**3.2 met**
Domestic activities	**Cooking**	**1.6 to 2.0 met**
	Washing dishes	**1.6 met**
	House cleaning	**2.0 to 3.4 met**
Dancing	**-**	**2.4 to 4.4 met**
Teaching	**-**	**1.6 met**
Games and sports	**Tennis, singles**	**3.6 to 4.0 met**
	Gymnastics	**4.0 met**
	Basket ball	**5.0 to 7.6 met**
	Wrestling	**7.0 to 8.7 met**

Studies show that the metabolic rate can be correlated to the rate of respiratory oxygen consumption and carbon dioxide production. Based on this empirical equations have been developed which relate metabolic rate to O_2 consumption and CO_2 production.

Since the metabolic rate is specified per unit area of the human body (naked body), it is essential to estimate this area to calculate the total metabolic rate. Even though the metabolic rate and heat dissipation are not uniform throughout the body, for calculation purposes they are assumed to be uniform.

The human body is considered to be a cylinder with uniform heat generation and dissipation. The surface area over which the heat dissipation takes place is given by an empirical equation, called as Du Bois Equation. This equation expresses the surface area as a function of the mass and height of the human being. It is given by:

$$A_{Du} = 0.202\, m^{0.425} h^{0.725} \qquad (29.3)$$

where A_{Du} = Surface area of the naked body, m^2
m = Mass of the human being, kg
h = Height of the human being, m

Since the area given by Du Bois equation refers to a naked body, a correction factor must be applied to take the clothing into account. This correction factor, defined as the "ratio of surface area with clothes to surface area without clothes" has been determined for different types of clothing. These values are available in ASHRAE handbooks. Thus from the metabolic rate and the surface area, one can calculate the amount of heat generation, Q_{gen}.

The total heat transfer rate from the skin Q_{sk} is given by:

$$Q_{sk} = \pm Q_{conv} \pm Q_{rad} + Q_{evp} \qquad (29.4)$$

where Q_{conv} = Heat transfer rate due to convection (sensible heat)
Q_{rad} = Heat transfer rate due to radiation (sensible heat), and
Q_{evp} = Heat transfer rate due to evaporation (latent heat)

The convective and radiative heat transfers can be positive or negative, i.e., a body may lose or gain heat by convection and radiation, while the evaporation heat transfer is always positive, i.e., a body always looses heat by evaporation. Using the principles of heat and mass transfer, expressions have been derived for estimating the convective, radiative and evaporative heat transfer rates from a human body. As it can be expected, these heat transfer rates depend on several factors that influence each of the heat transfer mechanism.

According to Belding and Hatch, the convective, radiative and evaporative heat transfer rates from the naked body of an average adult , Q_c, Q_r and Q_e, respectively, are given by:

$$\begin{aligned} Q_c &= 14.8\, V^{0.5} (t_b - t) \\ Q_r &= 11.603\, (t_b - t_s) \\ Q_e &= 181.76\, V^{0.4} (p_{s,b} - p_v) \end{aligned} \qquad (29.5)$$

In the above equation all the heat transfer rates are in watts, temperatures are in ^oC and velocity is in m/s; $p_{s,b}$ and p_v are the saturated pressure of water vapour at surface temperature of the body and partial pressure of water vapour in air, respectively, in kPa. From the above equations it is clear that the convective heat transfer from the skin can be increased either by increasing the surrounding air velocity (V) and/or by reducing the surrounding air DBT (t). The radiative heat transfer rate can be increased by reducing the temperature of the surrounding surfaces with which the body exchanges radiation. The evaporative heat transfer rate can be increased by increasing the surrounding air velocity and/or by reducing the moisture content of surrounding air.

The heat transfer rate due to respiration Q_{res} is given by:

$$\mathbf{Q_{res} = C_{res} + E_{res}} \qquad (29.5)$$

where C_{res} = Dry heat loss from respiration (sensible, positive or negative)
E_{res} = Evaporative heat loss from respiration (latent, always positive)

The air inspired by a human being is at ambient conditions, while air expired is considered to be saturated and at a temperature equal to the core temperature. Significant heat transfer can occur due to respiration. Correlations have been obtained for dry and evaporative heat losses due to respiration in terms of metabolic rate, ambient conditions etc.

For comfort, the rate of heat stored in the body Q_{st} should be zero, i.e.,

$$\mathbf{Q_{st} = 0 \ \text{at neutral condition}} \qquad (29.6)$$

However, it is observed that a human body is rarely at steady state, as a result the rate of heat stored in the body is non-zero most of the time. Depending upon the surroundings and factors such as activity level etc., the heat stored is either positive or negative. However, the body cannot sustain long periods of heat storage with a consequent change in body temperatures as discussed before.

Since the body temperature depends on the heat balance, which in turn depends on the conditions in the surroundings, it is important that the surrounding conditions should be such that the body is able to maintain the thermal equilibrium with minimum regulatory effort. All living beings have **in-built body regulatory processes against cold and heat**, which to some extent maintains the body temperatures when the external conditions are not favorable. For example, human beings consist of a thermoregulatory system, which tries to maintain the body temperature by initiating certain body regulatory processes against cold and heat.

When the environment is colder than the neutral zone, then body loses more heat than is generated. Then the regulatory processes occur in the following order.

1. Zone of vaso-motor regulation against cold (vaso-constriction): Blood vessels adjacent to the skin constrict, reducing flow of blood and transport of heat to the immediate outer surface. The outer skin tissues act as insulators.

2. Zone of metabolic regulation: If environmental temperature drops further, then vaso-motor regulation does not provide enough protection. Hence, through a spontaneous increase of activity and by shivering, body heat generation is increased to take care of the increased heat losses.

3. Zone of inevitable body cooling: If the environmental temperature drops further, then the body is not able to combat cooling of its tissues. Hence the body temperature drops, which could prove to be disastrous. This is called as zone of inevitable body cooling.

When the environment is hotter than the neutral zone, then body loses less heat than is generated. Then the regulatory processes occur in the following order.

1. Zone of vaso-motor regulation against heat (vaso-dilation): Here the blood vessels adjacent to the skin dilate, increasing the flow of blood and transport of heat to the immediate outer surface. The outer skin temperature increases providing a greater temperature for heat transfer by convection and radiation.

2. Zone of evaporative regulation: If environmental temperature increases further, the sweat glands become highly active drenching the body surface with perspiration. If the surrounding air humidity and air velocity permit, then increase in body temperature is prevented by increased evaporation from the skin.

3. Zone of inevitable body heating: If the environmental temperature increases further, then body temperature increases leading to the zone of inevitable body heating. The internal body temperature increases leading several ill effects such as heat exhaustion (with symptoms of fatigue, headache, dizziness, irritability etc.), heat cramps (resulting in loss of body salts due to increased perspiration) and finally heat stroke. Heat stroke could cause permanent damage to the brain or could even be lethal if the body temperature exceeds 43^{o}C.

Thus it is seen that even though human body possesses a regulatory mechanism, beyond certain conditions it becomes ineffective. Hence it is essential to ensure that surrounding conditions are conducive for comfortable and safe living. The purpose of a comfort air conditioning system is to provide suitable conditions in the occupied space so that it is thermally comfortable to the occupants.

A sedentary person at neutral condition loses about 40 % of heat by evaporation, about 30 % by convection and 30 % by radiation. However, this proportion may change with other factors. For example, the heat loss by evaporation increases when the DBT of the environment increases and/or the activity level increases

29.5. Factors affecting thermal comfort:

Thermal comfort is affected by several factors. These are:

1. Physiological factors such as age, activity, sex and health. These factors influence the metabolic rate. It is observed that of these factors, the most important is activity. Other factors are found to have negligible effect on thermal comfort.

2. Insulating factor due to clothing. The type of clothing has strong influence on the rate of heat transfer from the human body. The unit for measuring the resistance offered by clothes is called as "**clo**". 1 clo is equal to a resistance of about 0.155 $m^2.K/W$. Typical clo values for different types of clothing have been estimated and are available in the form of tables. For example, a typical business suit has a clo value of 1.0, while a pair of shorts has a clo value of about 0.05.

3. Environmental factors. Important factors are the dry bulb temperature, relative humidity, air motion and surrounding surface temperature. Of these the dry bulb temperature affects heat transfer by convection and evaporation, the relative humidity affects heat loss by evaporation, air velocity influences both convective and evaporative heat transfer and the surrounding surface temperature affects the radiative heat transfer.

Apart from the above, other factors such as drafts, asymmetrical cooling or heating, cold or hot floors etc. also affect the thermal comfort. The objective of a comfort air conditioning system is to control the environmental factors so that comfort conditions prevail in the occupied space. It has no control on the physiological and insulating factors. However, wearing suitable clothing may help in reducing the cost of the air conditioning system.

29.6. Indices for thermal comfort:

It is seen that important factors which affect thermal comfort are the activity, clothing, air DBT, RH, air velocity and surrounding temperature. It should be noted that since so many factors are involved, many combinations of the above conditions provide comfort. Hence to evaluate the effectiveness of the conditioned space, several comfort indices have been suggested. These indices can be divided into direct and derived indices. The direct indices are the dry bulb temperature, humidity ratio, air velocity and the mean radiant temperature (T_{mrt}).

The mean radiant temperature T_{mrt} affects the radiative heat transfer and is defined (in K) as:

$$\mathbf{T_{mrt}}^4 = \mathbf{T_g}^4 + \mathbf{CV}^{1/2}(\mathbf{T_g} - \mathbf{T_a}) \qquad (29.7)$$

where:

T_g = Globe temperature measured at steady state by a thermocouple placed at the center of a black painted, hollow cylinder (6" dia) kept in the conditioned space, K. The reading of thermocouple results from a balance of convective and radiative heat exchanges between the surroundings and the globe

T_a = Ambient DBT, K
V = Air velocity in m/s, and
C = A constant, 0.247×10^9

The derived indices combine two or more direct indices into a single factor. Important derived indices are the effective temperature, operative temperature, heat stress index, Predicted Mean Vote (PMV), Percent of People Dissatisfied (PPD) etc.

Effective temperature (ET): This factor combines the effects of dry bulb temperature and air humidity into a single factor. It is defined as the temperature of the environment at 50% RH which results in the same total loss from the skin as in the actual environment. Since this value depends on other factors such as activity, clothing, air velocity and T_{mrt}, a Standard Effective Temperature (SET) is defined for the following conditions:

Clothing	**=**	**0.6 clo**
Activity	**=**	**1.0 met**
Air velocity	**=**	**0.1 m/s**
$\mathbf{T_{mrt}}$	**=**	**DBT (in K)**

Operative temperature ($\mathbf{T_{op}}$): This factor is a weighted average of air DBT and T_{mrt} into a single factor. It is given by:

$$\mathbf{T_{op}} = \frac{\mathbf{h_r T_{mrt} + h_c T_{amb}}}{\mathbf{h_r + h_c}} \approx \frac{\mathbf{T_{mrt} + T_{amb}}}{\mathbf{2}} \qquad (29.8)$$

where h_r and h_c are the radiative and convective heat transfer coefficients and T_{amb} is the DBT of air.

ASHRAE has defined a comfort chart based on the effective and operative temperatures. Figure 29.3 shows the ASHRAE comfort chart with comfort zones for summer and winter conditions. It can be seen from the chart that the comfort zones are bounded by effective temperature lines, a constant RH line of 60% and dew point temperature of 2^{o}C. The upper and lower limits of humidity (i.e. 60 % RH and 2^{o}C DPT, respectively) are based on the moisture content related considerations of dry skin, eye irritation, respiratory health and microbial growth. The comfort chart is based on statistical sampling of a large number of occupants with activity levels less than 1.2 met. On the chart, the region where summer and winter comfort zones overlap, people in winter clothing feel slightly warm and people in summer clothing feel slightly cool. Based on the chart ASHARE makes the following recommendations:

Inside design conditions for Winter:

T_{op} between 20.0 to 23.5^{o}C at a RH of 60%

T_{op} between 20.5 to 24.5^{o}C at a DPT of 2^{o}C

Inside design conditions for Summer:

T_{op} between 22.5 to 26.0^{o}C at a RH of 60%

T_{op} between 23.5 to 27.0^{o}C at a DPT of 2^{o}C

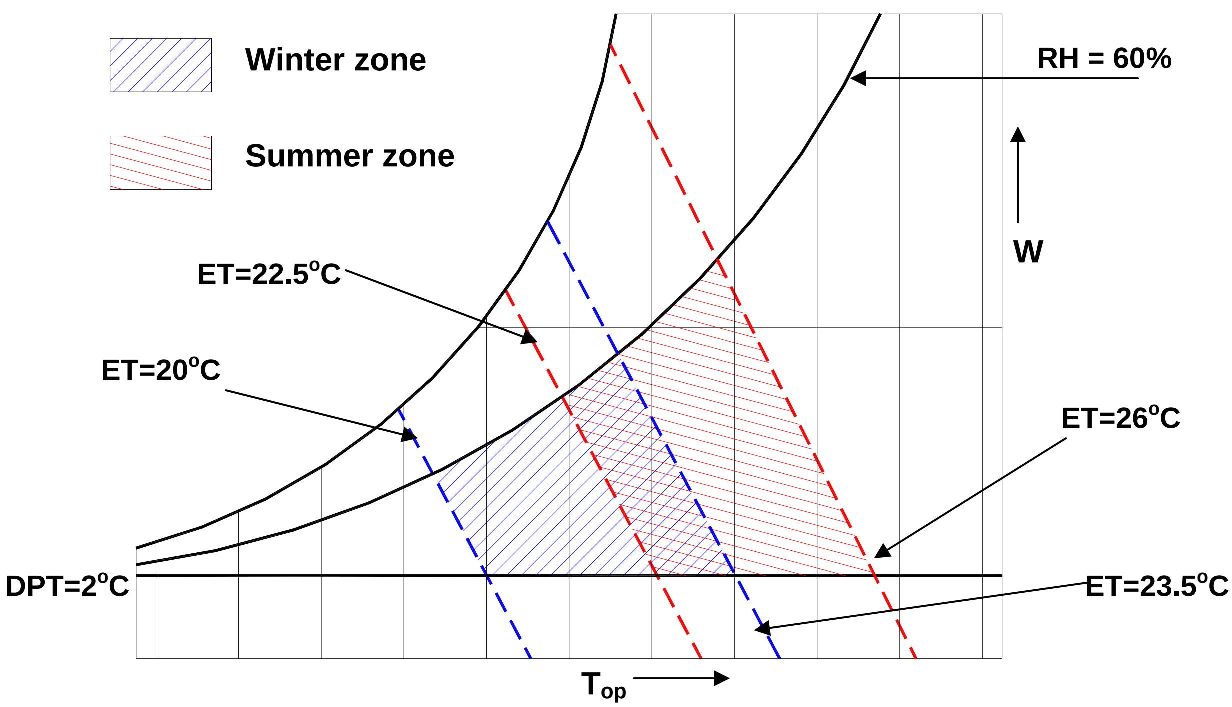

***Fig.29.3**: ASHRAE comfort chart for a sedentary person (activity ≈ 1.2 met)*

Table 29.2 shows the recommended comfort conditions for different seasons and clothing suitable at 50 % RH, air velocity of 0.15 m/s and an activity level of ≤ 1.2 met.

Season	Clothing	I_{cl}	$T_{op,opt}$	T_{op} range for 90% acceptance
Winter	Heavy slacks, long sleeve shirt and sweater	**0.9 clo**	**22°C**	**20 to 23.5 °C**
Summer	Light slacks and short sleeve shirt	**0.5 clo**	**24.5°C**	**23 to 26°C**
	Minimal (shorts)	**0.05 clo**	**27°C**	**26 to 29 °C**

***Table 29.2**: Optimum and recommended operative temperatures for comfort*

The above values may be considered as recommended inside design conditions for comfort air conditioning. It will be shown later that the **cost of air conditioning (initial plus running) increases as the required inside temperature increases in case of winter and as the required inside condition decreases in case of summer**. Hence, air conditioning systems should be operated at as low a temperature as acceptable in winter and as high a temperature as acceptable in summer. Use of suitable clothing and maintaining suitable air velocities in the conditioned space can lead to reduced cost of air conditioning. For example, in summer the clothing should be minimal at a socially acceptable level, so that the occupied space can be maintained at higher temperatures. Similarly, by increasing air velocity without causing draft, one can maintain the occupied space at a higher temperature in summer. Similarly, the inside temperatures can be higher for places closer to the equator (1°C rise in ET is allowed for each 5° reduction in latitude). Of course, the above recommendations are for normal activities. The required conditions change if the activity levels are different. For example, when the activity level is high (e.g. in gymnasium), then the required indoor temperatures will be lower. These special considerations must be kept in mind while fixing the inside design conditions. Prof. P.O. Fanger of Denmark has carried out pioneering and detailed studies on thermal comfort and suggested comfort conditions for a wide variety of situations.

29.6.1. Predicted Mean Vote (PMV) and Percent People Dissatisfied (PPD):

Based on the studies of Fanger and subsequent sampling studies, ASHRAE has defined a thermal sensation scale, which considers the air temperature, humidity, sex of the occupants and length of exposure. The scale is based on empirical equations relating the above comfort factors. The scale varies from +3 (**hot**) to –3 (**cold**) with 0 being the neutral condition. Then a Predicted Mean Vote (PMV) that predicts the mean response of a large number of occupants is defined based on the thermal sensation scale.

The PMV is defined by Fanger as:

$$\mathbf{PMV = [0.303\,exp(-0.036M) + 0.028]L} \qquad (29.9)$$

where M is the metabolic rate and L is the thermal load on the body that is the difference between the internal heat generation and heat loss to the actual environment of a person experiencing thermal comfort. The thermal load has to be obtained by solving the heat balance equation for the human body.

Fanger related the PMV to Percent of People Dissatisfied (PPD) by the following equation:

$$\mathbf{PPD = 100 - 95\,exp[-(0.03353\ PMV^4 + 0.2179\ PMV^2)]} \qquad (29.10)$$

where dissatisfied refers to anybody not voting for –1, 0 or +1. It can be seen from the above equation that even when the PMV is zero (i.e., no thermal load on body) 5 % of the people are dissatisfied! When PMV is within $\pm$ 0.5, then PPD is less than 10 %.

Of late, several studies have been carried out on adaptive thermal comfort. These studies show that human beings adapt to their natural surroundings so as to feel thermally comfortable. The adaptation consists of changing their clothing, activity level and schedule, dietary habits etc. according to the surrounding conditions. Due to this human tendency, it is observed that human beings feel comfortable that are higher or lower than those suggested by the heat balance equation as outlined by Fanger. It is observed that there is correlation between the outside temperatures and the required inside temperatures at which human beings feel comfortable, or at least do not feel uncomfortable. For example, a study by Humphrey on adaptive thermal comfort in tropical countries suggests the following correlation for comfort temperature in free-running (non-air conditioned) buildings:

$$\mathbf{T_c = 0.534T_o + 12.9} \qquad (29.11)$$

Where T_o and T_c are the outdoor and indoor comfort temperature in ^oC, respectively. According to the above correlation, higher the outdoor temperature, higher can be the indoor temperature. This is very important from energy conservation point-of-view as air conditioning systems are very energy intensive, and the load on an air conditioning plant can be reduced by maintaining the indoor temperatures at as high a value as is allowed from thermal comfort point-of-view.

29.7. Selection of outside design conditions:

The ambient temperature and moisture content vary from hour-to-hour and from day-to-day and from place-to-place. For example, in summer the ambient temperature increases from sunrise, reaches a maximum in the afternoon and again decreases towards the evening. On a given day, the relative humidity also varies with temperature and generally reaches a minimum value when the ambient temperature is maximum. For most of the major locations of the world, meteorological data is available in the form of mean daily or monthly maximum and minimum temperatures and corresponding relative humidity or wet bulb temperature. As mentioned before, to estimate the required cooling capacity of an air conditioning plant, it is essential to fix the outside design conditions in addition to the inside conditions. It is obvious that the selected design conditions may prevail only for a short a duration, and most of the time the actual outside conditions will be different from the design values. As a result, for most of the time the plant will be running at off-design conditions.

The design outside conditions also depend on the following factors:

a) Type of the structure, i.e., whether it is of heavy construction, medium or light
b) Insulation characteristics of the building
c) Area of glass or other transparent surfaces
d) Type of usage
e) Nature of occupancy
f) Daily range (difference between maximum and minimum temperatures in a given day)

29.7.1. Outdoor design conditions for summer:

Selection of maximum dry and wet bulb temperatures at a particular location leads to excessively large cooling capacities as the maximum temperature generally persists for only a few hours in a year. Hence it is recommended that the outdoor design conditions for summer be chosen based on the values of dry bulb and mean coincident wet bulb temperature that is equaled or exceeded 0.4, 1.0 or 2.0 % of total hours in an year. These values for major locations in the world are available in data books, such as AHRAE handbooks. Whether to choose the 0.4 % value or 1.0 % value or 2.0 % value depends on specific requirements. In the absence of any special requirements, the 1.0% or 2% value may be considered for summer outdoor design conditions.

29.7.2. Outdoor design conditions for winter:

Similar to summer, it is not economical to design a winter air conditioning for the worst condition on record as this would give rise to very high heating capacities. Hence it is recommended that the outdoor design conditions for winter be chosen based on the values of **dry bulb temperature** that is **equaled or exceeded 99.6 or 99.0 % of total hours in an year**. Similar to summer design conditions, these values for major locations in the world are available in data books, such as AHRAE handbooks. Generally the 99.0% value is adequate, but if the building is made of light-weight materials, poorly insulated or has considerable glass or space temperature is critical, then the 99.6% value is recommended.

Table 29.3 shows the ASHRAE recommended summer design conditions for major Indian cities. In the table DB stands for the design DBT and MWB stands for mean coincident WBT.

City	0.4% value		1.0% value		2.0% value		Daily range
	DB	MWB	DB	MWB	DB	MWB	
Ahmadabad	42.2°C	23.3°C	41.1°C	23.3°C	39.4°C	23.9°C	12.7°C
Bangalore	34.4°C	19.4°C	33.3°C	19.4°C	32.8°C	19.4°C	10.7°C
Bombay	35.0°C	22.8°C	33.9°C	23.3°C	33.3°C	23.9°C	5.2°C
Calcutta	37.2°C	25.6°C	36.1°C	26.1°C	35.0°C	26.1°C	10.0°C
Hyderabad	40.6°C	21.7°C	39.4°C	21.7°C	39.4°C	21.7°C	10.5°C
Jaipur	42.2°C	20.6°C	40.6°C	20.6°C	39.4°C	20.6°C	12.4°C
Madras	38.3°C	25.0°C	37.2°C	25.0°C	36.1°C	25.0°C	8.1°C
Nagpur	43.3°C	21.7°C	42.2°C	21.7°C	41.1°C	21.7°C	12.7°C
New Delhi	41.7°C	22.2°C	40.6°C	22.2°C	39.4°C	22.8°C	12.0°C
Poona	37.8°C	19.4°C	37.2°C	19.4°C	36.1°C	19.4°C	16.1°C
Trivendrum	33.3°C	25.6°C	32.8°C	25.6°C	32.2°C	25.6°C	6.5°C

***Table 29.3**: Design summer outside conditions for some Indian cities (ASHRAE)*

Questions and answers:

1. Which of the following statements are TRUE?

a) The metabolic rate depends mainly on age of the human being
b) The metabolic rate depends mainly on the activity level of the human being
c) The metabolic rate depends mainly on the sex of the human being
d) All of the above

Ans.: b)

2. Which of the following statements are TRUE?

a) To maintain thermal comfort, the DBT of air should be increased as its moisture content increases
b) To maintain thermal comfort, the DBT of air should be decreased as air velocity increases
c) To maintain thermal comfort, the DBT of air should be increased as the temperature of the surrounding surfaces decrease
d) All of the above

Ans.: c)

3. Which of the following statements are TRUE?

a) Surrounding air velocity affects convective heat transfer from the body only
b) Surrounding air velocity affects evaporative heat transfer from the body only
c) Surrounding air velocity affects both convective and evaporative heat transfers from the body
d) Moisture content of the air affects both convective and evaporative heat transfers from the body

Ans.: c)

4. Which of the following statements are TRUE?

a) As the amount of clothing increases, the surrounding DBT should be increased to maintain thermal comfort
b) As the amount of clothing increases, the surrounding DBT should be decreased to maintain thermal comfort
c) As the activity level increases, DBT of air should be increased to maintain thermal comfort
d) As the activity level increases, DBT of air should be decreased to maintain thermal comfort

Ans.: b) and d)

5. Which of the following statements are TRUE?

a) Effective temperature combines the affects of dry bulb temperature and air velocity into a single index
b) Effective temperature combines the affects of dry bulb temperature and wet bulb temperature into a single index
c) Mean radiant temperature combines the affects of dry bulb temperature and surrounding surface temperature into a single index
d) Operative temperature combines the affects of dry bulb temperature and mean radiant temperature into a single index

Ans.: b) and d)

6. From ASHRAE comfort chart it is observed that:

a) Lower dry bulb temperatures and higher moisture content are recommended for winter
b) Lower dry bulb temperatures and lower moisture content are recommended for winter
c) Lower dry bulb temperatures and higher moisture content are recommended for summer
d) Higher dry bulb temperatures and higher moisture content are recommended for summer

Ans.: b) and d)

7. Which of the following statements are TRUE?

a) For the same metabolic rate, as the thermal load on human body increases, the PMV value increases
b) For the same metabolic rate, as the thermal load on human body increases, the PMV value decreases
c) As the absolute value of PMV increases, the percent of people dissatisfied (PPD) increases
d) As the absolute value of PMV increases, the percent of people dissatisfied (PPD) decreases

Ans.: a) and c)

8. Which of the following statements are TRUE?

a) When a human body is at neutral equilibrium, the PMV value is 1.0
b) When a human body is at neutral equilibrium, the PMV value is 0.0
c) When a human body is at neutral equilibrium, the PPD value is 0.0
d) When a human body is at neutral equilibrium, the PPD value is 5.0
Ans.: b) and d)

9. Which of the following statements are TRUE?

a) The air conditioning load on a building increases, if 0.4% design value is used for outside conditions instead of 1.0% value for summer
b) The air conditioning load on a building decreases, if 0.4% design value is used for outside conditions instead of 1.0% value for summer
c) For winter air conditioning, a conservative approach is to select 99.6% value for the outside design conditions instead of 99% value
d) For winter air conditioning, a conservative approach is to select 99% value for the outside design conditions instead of 99.6% value

Ans.: a) and c)

10. A 1.8 meter tall human being with a body mass of 60 kg performs light work (activity = 1.2 met) in an indoor environment. The indoor conditions are: DBT of 30^{o}C, mean radiant temperature of 32^{o}C, air velocity of 0.2 m/s. Assuming an average surface temperature of 34^{o}C for the surface of the human being and light clothing, find the amount of evaporative heat transfer required so that the human being is at neutral equilibrium.

Ans.: Using Du Bois equation, the surface area of the human being A_s is:

$$\mathbf{A_{Du} = 0.202\,m^{0.425}h^{0.725} = 0.202 \times 60^{0.425} \times 1.8^{0.725} = 1.7625\ m^2}$$

Hence the total heat generation rate from the body, Q_g is:

$$\mathbf{Q_g = A_s \times (Activity\ level\ in\ met) \times 58.2 = 1.7625 \times 1.2 \times 58.2 = 123.1\ W}$$

Using Belding & Hatch equations, the convective and radiative heat losses from the surface of the body are found as:

$$\mathbf{Q_c = 14.8\,V^{0.5}(t_b - t) = 14.8 \times 0.2^{0.5}(34-30) = 26.48\,W}$$
$$\mathbf{Q_r = 11.603\ (t_b - t_s) = 11.603(34-32) = 23.2\,W}$$

For neutral equilibrium,

$$\mathbf{Q_g = Q_c + Q_r + Q_e = \Rightarrow Q_e = Q_g - (Q_c + Q_r)}$$

Substituting the values of Qg, Qc and Qr in the above expression, we find that the required amount of evaporative heat transfer Qe is equal to:

$$\mathbf{Q_e = 123.1 - (26.48+23.2) = 73.42\ W \qquad (Ans.)}$$