Chapter Four

Thermal Comfort

One of the main purposes of an air-conditioning system is to provide conditions for human thermal comfort. Comfort is related to levels of optimum acceptability which has been established by response tests for all types of subjects under varying environmental conditions of temperature and humidity. It is a subjective quality, personal to individuals depending on sex, age, state of health, clothing, environmental conditions, and very often depending on individual preferences. In general, comfort occurs when body temperatures are held within narrow ranges, and skin moisture is low. The level of noise in the controlled environment also affects the feeling of comfort.

4.1 Heat Balance Equation

The physical basis of comfort lies in the thermal balance of the body, i.e. the heat produced by the body's metabolism must be dissipated to the environment, otherwise the body would overheat.

The total energy production rate of the body is the sum of the production rates of heat $\dot{Q}$ and work $\dot{W}$ and can be written in the form

$$\dot{Q} + \dot{W} = MA_{skin} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.1)$$

Where

M is the rate of metabolic energy production per unit surface area

A_{skin} is the total surface area of skin.

The thermal balance of the body can be expressed by the equation,

$$S = (M - W) - E \pm R \pm C \quad \ldots\ldots\ldots\ldots\ldots\ldots (4.2)$$

Where

(M – W) is the net surplus heat to be liberated or stored (metabolic rate minus the useful rate of working)

E is the heat loss by evaporation

R is the heat gain or loss by radiation

C is the heat gain or loss by convection

S is the rate at which heat is stored within the body.

Under steady state conditions, the body remains comfortable and healthy because S is zero. In an oppressively hot environment, the load imposed upon E, R and C may be so great that S is positive and the body temperature will rise, eventually resulting in heat stroke.

Heat dissipation from the body (Table 4.1) to immediate surroundings occurs by several modes of heat exchange:

- Sensible heat flow from the skin
- Latent heat flow from evaporation of sweat and from evaporation of moisture diffused through the skin
- Sensible heat flow during respiration
- Latent heat flow due to evaporation of moisture during respiration.

Table 4.1 Heat output of the body in various activities

Activity	Watts
Sleeping	min. 70
Sitting, moderate movement, e.g. typing on computer	160 – 190
Sitting, heavy arm and leg movements	190 – 230
Standing, moderate work, some walking	220 – 290
Walking, moderate lifting or pushing	290 – 410
Intermittent heavy lifting, digging	440 – 580
Hard, sustained work	580 – 700

Sensible and latent heat losses from the skin are typically expressed in terms of environmental factors, skin temperature, and skin wettedness. The main independent environmental variables can be summarized as air temperature, mean radiant temperature and relative air velocity and ambient water vapor pressure.

4.2 Thermal Interchange with Environment

The human body is continually gaining and producing heat as well as losing heat to its surroundings to maintain temperature equilibrium. Body heat gains come from two source:

- Heat produced within the body itself as a result of metabolic processes.

- Heat gained by body from external sources, by radiation from the sun or other hot objects or surfaces, and by convection from the surrounding air.

Heat is lost from the body by:

(a) **Conduction:** Heat loss by conduction depends on the temperature difference between the body surface and the object with which the body is in direct contact. Heat lost by conduction from the body can be neglected as the amount of body surface in contact with an external surface is usually too small and the period of contact is short too.

(b) **Convection** (about 30%): Heat loss due to convection takes place from the body to the air in contact with the skin or clothing. The rate of convection heat loss is increased by a faster rate of air movement, by a lower air temperature and a higher skin temperature.

(c) **Radiation** (about 45%): Radiant heat loss depends on the temperature of the body surface and the temperature of the opposing surfaces. Thus the human body will radiate heat to walls, ceilings, floors, windows, and to the out of doors if these surfaces are at a lower temperature than the body surface. Conversely, the body gains by radiation from the sun or from any surface warmer than the skin surface. Body skin temperature ranges between 30ºC and 34ºC with an average of 32.2ºC for a healthy person engaged in light activity.

(d) **Evaporation** (about 25%): Heat loss by evaporation fan is governed by the rate of evaporation, which in turn depends on the humidity of air (the dryer the air, the faster the evaporation) and on the amount of moisture available for evaporation.

Metabolic heat generation

In choosing optimal conditions for comfort and health, knowledge of the energy expended during the course of routine physical activities is necessary, since heat production increases in proportion to exercise intensity. The unit used to measure the metabolic rate is *met*. One met represents the average heat produced by a sedentary average person at normal mean radiant temperature, i.e. 1 met = 58.2 W/m^2. Table 4.2 lists the typical metabolic heat generation for various activities.

Table 4.2 Typical metabolic heat generation for various activities

Activities	W/m^2	met
Resting		
Sleeping	40	0.7
Reclining	45	0.8
Seated, quiet	60	1.0
Standing, relaxed	70	1.2
Walking		
3.2 km/h (0.9 m/s)	115	2.0
4.3 km/h (1.2 m/s)	150	2.6
6.4 km/h (1.8 m/s)	220	3.8
Office activities		
Reading, seated	55	1.0
Writing	60	1.0
Typing	65	1.1
Filing, seated	70	1.2
Filing, standing	80	1.4
Walking about	100	1.7
Lifting/packing	120	2.1

Clothing affects comfort, since it acts as an insulation. The unit measuring the insulating effect of clothing on a human subject is *clo*, where, 1 *clo* = 0.155 km^2/W.

4.3 Environmental Parameters and Indices

Environmental parameters

Environmental parameters that affect human comfort can be categorized into (a) directly measured parameters and (b) calculated parameters.

The following are the frequently used directly measured psychrometric parameters:

- Dry bulb temperature
- Wet bulb temperature
- Dew point temperature
- Water vapor pressure
- Total atmospheric pressure
- Relative humidity
- Humidity ratio
- Air velocity

The mean radiant temperature is derivable and, hence, a *calculated parameter*. It is the temperature of a uniform black enclosure in which a solid body or occupant would exchange the same amount of radiant heat as in the existing non-uniform environment. Fanger identified two additional calculated parameters, which are *activity level* and *clothin*g. In addition to the above, the other secondary factors such as day-to-day temperature variation, age, adaptability, sex, etc. also influence comfort.

Environmental indices

An environmental index combines two or more parameters, such as air temperature, mean

radiant temperature, humidity or air velocity into a single variable. The *effective temperature* (ET^*) is probably the most common environmental index and has the widest range of applications.

The *effective temperature* (ET^*) is defined as the dry bulb temperature of a uniform enclosure at 50% RH in which humans would have the same net heat exchange by radiation, convection, and evaporation as they would in the varying humidities of the test environment.

Another approach used to evaluate the combined effect of temperature and humidity is *the Heat Stress Index*. This index is the ratio of the total evaporative heat loss required for thermal equilibrium to the maximum evaporative heat loss possible for the environment, multiplied by 100 for steady-state conditions (skin temperature is held constant at 35ºC in order to limit the rise in body temperature, the sweat rate should not exceed one liter per hour to limit the loss of body fluid). The heat stress index is therefore defined as

$$\text{Heat Stress Index} = \dot{Q}_E / \dot{Q}_{E,max} \quad \text{……………………….. (4.3)}$$

Where

$\dot{Q}_E$ is the actual evaporative loss

$\dot{Q}_{E,max}$ is the maximum evaporative heat loss with the skin temperature at 35ºC.

4.4 Comfort Charts

In identical environments, different people perceive comfort in different ways. In the same built environment, some may feel chilly while others may feel warm. Dry bulb temperature is not a reliable indication of how warm or cold an occupant will feel in a room. The effects of both relative humidity and air velocity need also to be considered.

In the same context, ASHRAE and other researchers have conducted extensive research over the years to relate the above factors to human comfort. From the results of these tests emerged the concept of an *effective temperature*. This index is a measure of comfort which involves the combined effect of dry bulb, wet bulb, and air movement as judged by the subjects in the research studies. There were a number of different combinations of dry bulb and relative humidity which would give the same feeling of comfort to a high percentage of the subjects for a given air velocity.

A typical comfort chart shown in Figure 4.1 could then be constructed by drawing lines through the points at which the majority of people equally clothed and equally active reported the same feeling of comfort. These lines are called the *effective temperature* (ET) lines.

The range of the summer effective temperatures from around 19 to 24ºC, while the range of the effective temperatures are from 17ºC to 22ºC.

Over the years a number of similar charts have been developed by ASHRAE and other researchers including Fanger who developed General Comfort Charts based on clothing, activities, air temperatures, etc.

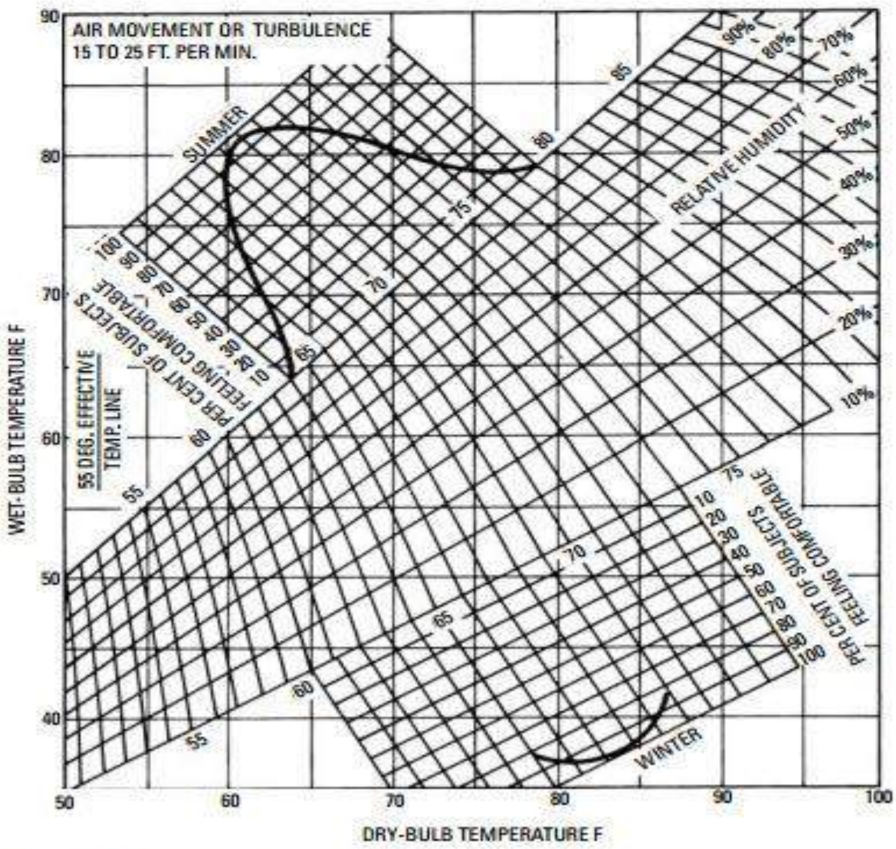
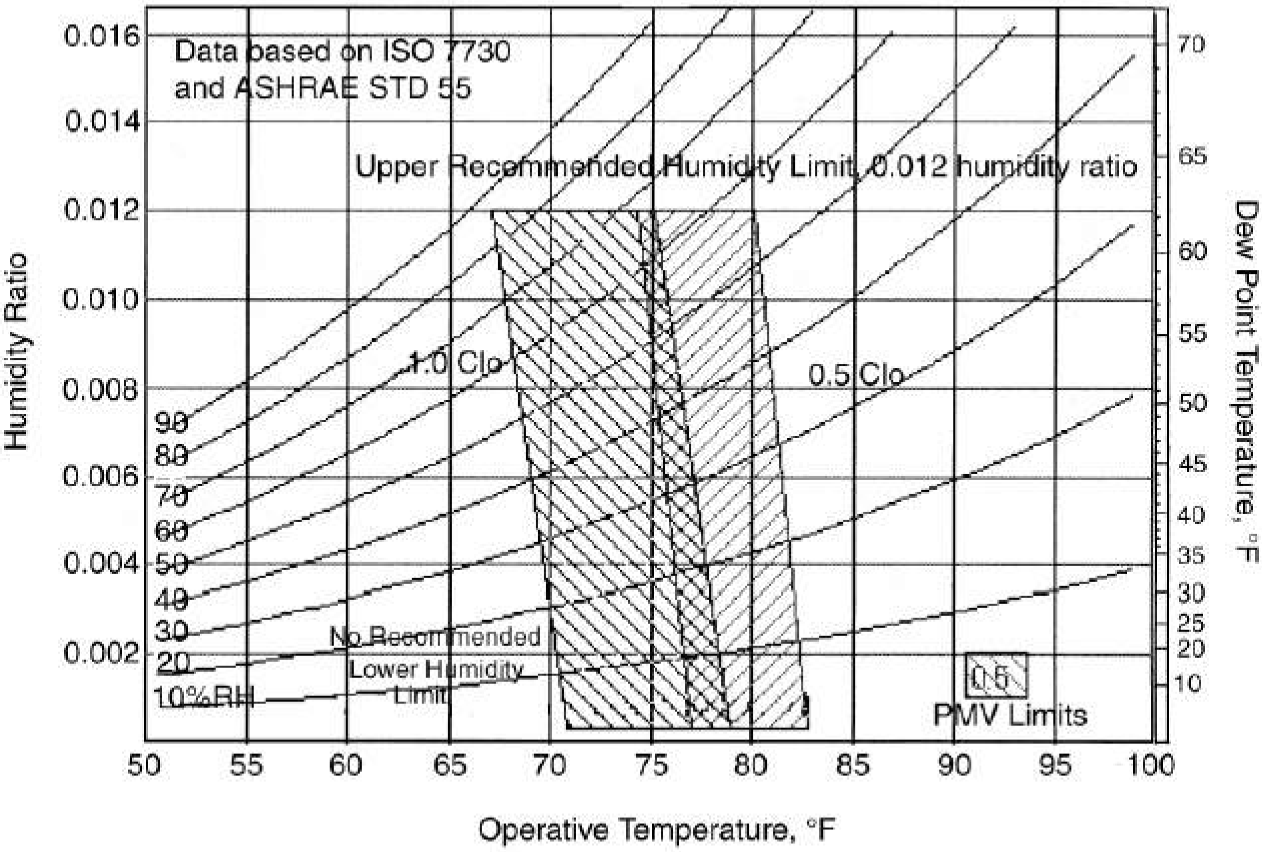


Figure 8-8 Comfort chart for still air. *(Courtesy ASHRAE 1960 Guide)*

(a) Comfort chart for still air



(b) ASHRAE comfort zones for summer and winter

Figure 4.1 (a) Comfort chart for still air (b) ASHRAE comfort zones for summer and winter.

4.5 Prediction of Thermal Comfort

Human thermal is influenced by physiological factors, it is difficult to specify a single quantity for evaluating human comfort. The usual comfort parameters are ambient air temperature, humidity, air motion, body activity level, and clothing. However, it has been observed that if the surrounding surfaces are below the air dry bulb temperature, comfort would occur at a higher effective temperature than that indicated by Fig. 4.1. This implies that radiant cooling affects comfort parameters/sensation appreciably. Studies have also indicated that women of all ages prefer an effective temperature about one degree higher than that preferred by men, while both men and women over 40 years age prefer an effective temperature about one degree higher than that desired by younger people. People of all climatic regions have identical preferred temperatures. The activity level of the occupants and the duration of occupancy also affect human thermal comfort sensation.

Thermal comfort and thermal sensation can be predicted by (a) a comfort chart and (b) numerically by the predicted mean vote (**PMV**) and the predicted percentage of dissatisfied

(**PPD**). The predicted mean vote predicts the mean response of a large group of people. This comfort sensation scale as developed by Rohles and Nevins is shown in Table 4.3.

Table 4.3 ASHRAE thermal sensation scale

+3	Hot
+2	Warm
+1	Slightly warm
0	Neutral
-1	Slightly cool
-2	Cool
-3	Cold

The test results have been correlated with the dry bulb temperature, humidity level, sex, and duration of exposure. The basic equation used to compute the **PMV** is

$$PMV = a^{*}t + b^{*}p_v + c^{*} \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (4.4)$$

Where, **t** is the dry bulb temperature (°C) and $\mathbf{p_v}$ is the corresponding saturation pressure (kPa). a^*, b^* and $c^*$are the coefficients used for calculating PMV. The values of a^*, b^* and c^*, can be obtained from Table 4.4.

Table 4.4 Coefficient a^*, b^* and c^* used to calculate the predicted mean vote (PMV)

Exposure period (hr)	Sex	a^*	b^*	c^*
1.0	Male	0.220	0.233	-5.673
1.0	Female	0.272	0.248	-7.245
1.0	Combined	0.245	0.248	-6.475
3.0	Male	0.212	0.293	-5.949
3.0	Female	0.275	0.255	-8.622
3.0	Combined	0.243	0.278	-6.802

For young adult subjects with sedentary activity and wearing clothing with a thermal resistance of approximately 0.5 clo, air velocity (0.2 m/s).

After calculating the PMV, the PPD is estimated for the same condition (Fig. 4.2). The dissatisfied occupants are defined as those who do not vote either +1, 0 or -1 on the PMV scale. The PMV- PPD model is widely used and accepted for design and field assessment of comfort conditions.

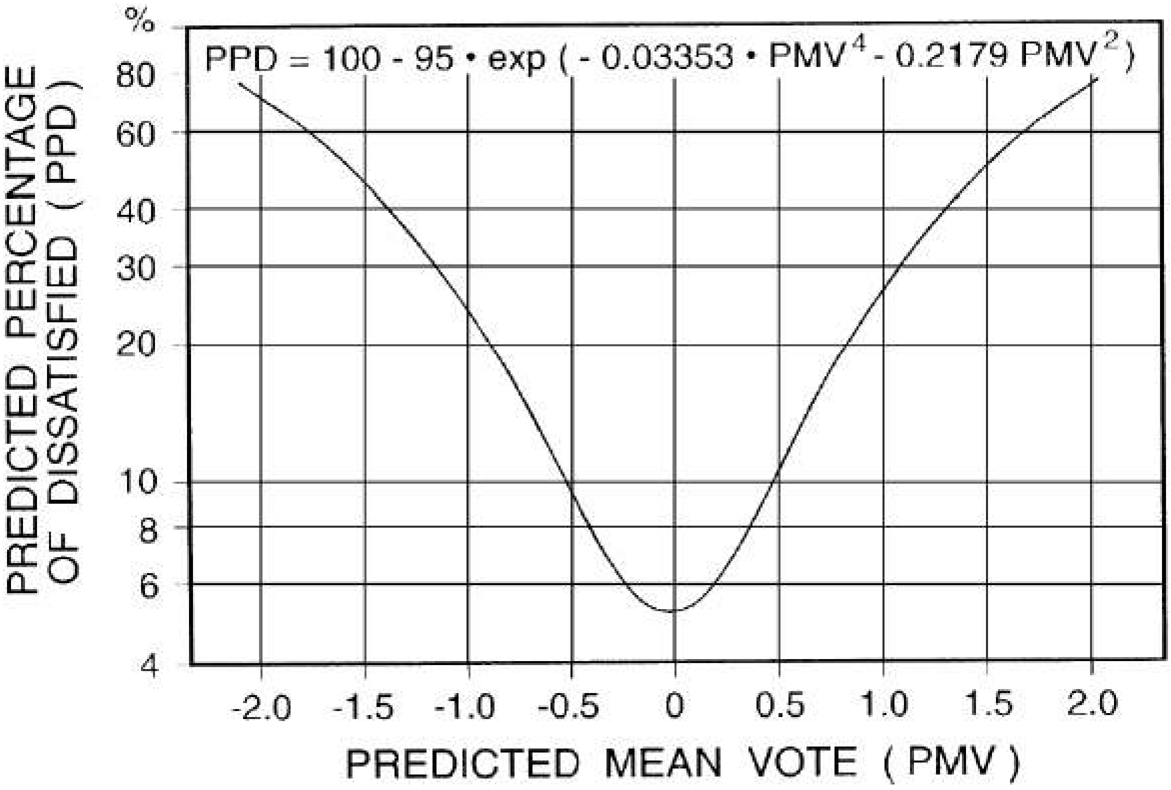


Figure 4.2 PPD as a function of PMV

Example 4.1:

A number of male and female subjects took part in a climate chamber test. Determine the difference between the PMV of male and that of female occupants with the dry bulb temperature being 24°C and the dew point temperature being 20°C, one hour after entry into the space.

Solution:

$$PMV = a^{*}t + b^{*}p_{v} + c^{*}$$

PMV for men:

$$PMV= 0.22(24) + 0.233(2.339) – 5.673 = 0.051$$

Similarly, PMV for women:

PMV = 0.272(24) + 0.248(2.339) – 7.245 = - 0.136

From the above, both males and females are predicted to be thermally neutral.

The P_v values can be obtained from the table of thermodynamic properties of water at saturation.

4.6 Indoor Design Conditions

The most commonly recommended design conditions for comfort are:

ET^*= 24°C

Dry bulb temperature = mean radiant temperature

Relative humidity = 50% (30 – 70)%

Air velocity less than 0.2 m/s

The indoor conditions to be maintained within a building are the dry bulb temperature and relative humidity of the air at the breathing line, 1 to 1.5 m above the floor, in an area that would indicate average condition at that level and which would not be affected by abnormal or unusual heat gains or losses from the interior or exterior.

Table 4.5 shows the guideline room air temperatures for different applications.