Chapter Three

Thermal Comfort

1. Introduction.
2. Basic concepts of thermal comfort.
3. Thermal balance of the human body.
4. Factors affecting thermal comfort.
5. The thermal indices.
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6. Tests and Exercises.

1. Introduction

Knowledge of the nature of comfort is essential in design with climate. The human body maintains a thermal balance by controlling heat loss and gain. The six major factors that affect comfort are the air temperature, the mean radiant temperature, the air velocity, the relative humidity, the intrinsic clothing and the level of activity. Thermal indices indicate the simultaneous effect of these six variables on comfort. Such indices include the Standard Effective Temperature (SET), the Effective Temperature (ET), the Corrected Effective Temperature (CET), the Resultant Temperature (RT), the Heat Stress Index (HSI), the Equivalent Warmth (EW), the Equatorial Comfort Index (ECI), the Predicted Four Hour Sweat Rate (P4SR), the Operative Temperature (OT), the Index of Thermal Stress (ITS), the Bioclimatic Chart, the Mahoney Scale and the Evans Scale. Only some of these indices may be applicable in Nigerian conditions.

2. Basic Concepts of Thermal Comfort.

The aim of design with climate is to maintain comfort within buildings. The climatic data earlier described give us a more or less accurate idea of the external conditions, that is the conditions that exist outside the enclosure in question. An analysis is usually carried out to ascertain how these external conditions compare with the required conditions. It is essential in this respect to define the limits within which people are likely to feel comfortable. Knowledge of these limits will be used to determine the degree of discomfort and the conditions such as the humidity and the temperature range, which are experienced simultaneously with uncomfortable or hot temperatures.

The subjective nature of comfort must be stressed. It is not possible to achieve conditions in which everybody will be comfortable. The best comfort conditions are called optimum thermal conditions. Under these conditions about 50 to 75% of people feel comfortable.

3. Thermal Balance of the Human Body

The body gets energy from digestion of food through metabolism, that is the processes involved in converting foodstuff into living matter and energy.

There are two types of metabolism:

Basal metabolism, which is the heat production of vegetative, automatic, processes which are continuous -breathing, digestion and circulation of blood.

Muscular metabolism, which is the heat production of muscles while carrying out some work or activity.

The body is not very efficient in turning chemical energy into physical energy and about 80% of the energy produced must be dissipated in form of heat. Apart from basal and muscular metabolism, the body can gain heat by conduction, convection and radiation from the environment. The heat from the body can be lost

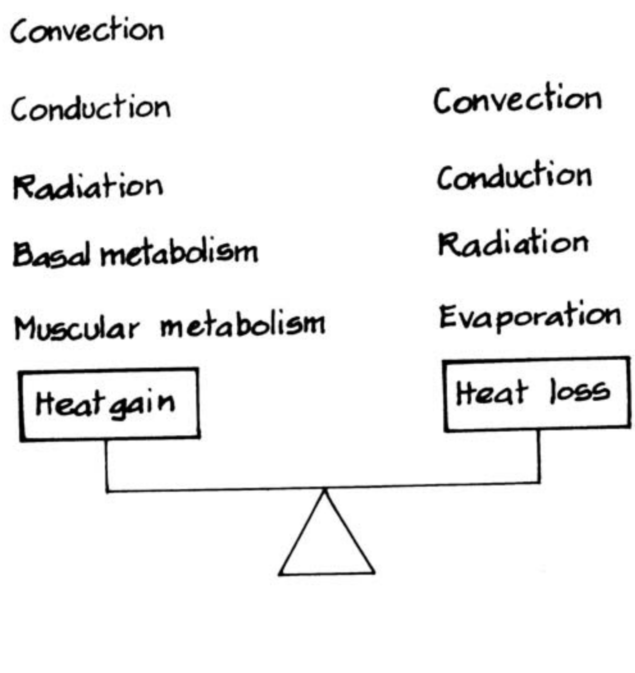

Figure 1: Thermal balance of the human body.

through conduction, convection, radiation and evaporation.

In order to maintain a constant deep body temperature and thermal balance, the total heat gained must be equal to the total heat lost. See figure 1.

There are mechanisms for controlling heat loss both inside and outside the body. These include sweating, shivering, and breathing. Control is maintained externally by clothing, activity rate, posture and choice of location. These are individual voluntary control mechanisms. See figures 2 and 3. The physical built environment can also affect the thermal environment, thereby contributing to the control of body temperature.

4. Factors Affecting Thermal Comfort

There are six major factors which affect thermal comfort. They are:

- the air temperature
- the mean radiant temperature
- the air velocity
- the relative humidity
- the intrinsic clothing
- the level of activity

The first four are factors of the thermal environment. Apart from these major factors, there are several others that may have an effect on the sensation of comfort. These include age, sex, acclimatisation, body shape and health.

Air Temperature

The air temperature, that is the dry bulb temperature is a very important factor affecting thermal comfort. When temperatures are low, people feel cold and when they are high people feel hot. Comfort can approximately be achieved between 16 and 28 degrees Celsius.

The Mean Radiant Temperature

This refers usually to radiation to and from surfaces within an enclosure measured with the globe thermometer. The mean radiant temperature is calculated from the globe temperature using the air temperature and velocity. Comfort can be achieved if the globe temperature is between 16 and 28 degrees Celsius and if the difference between the mean

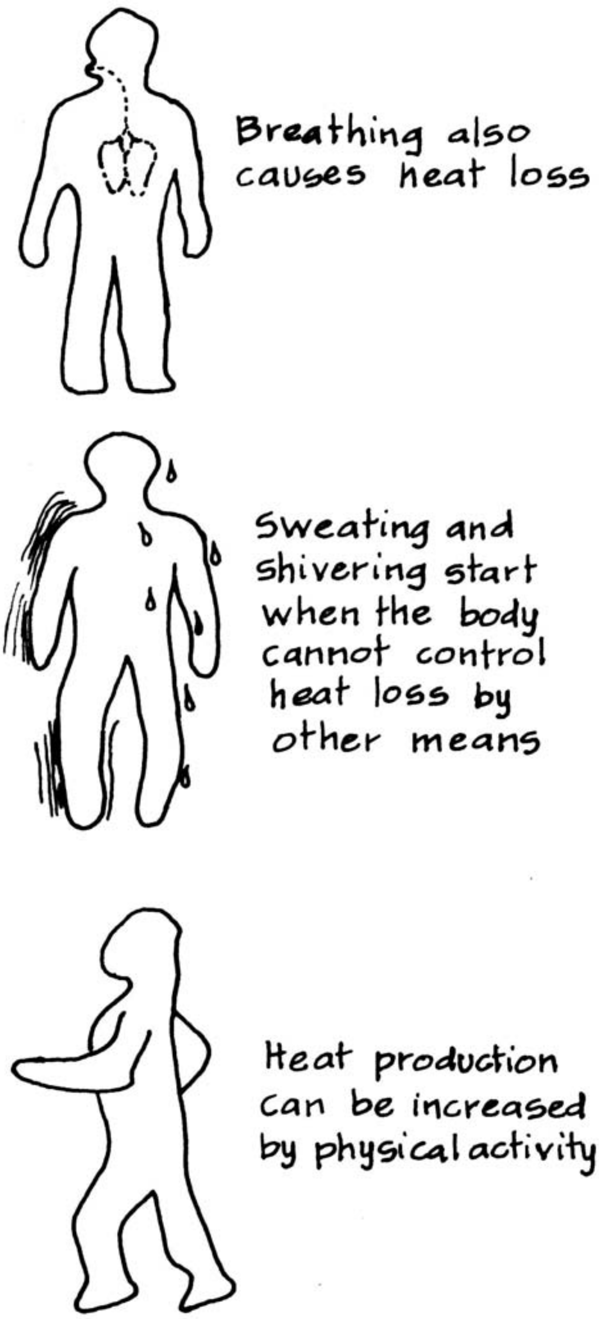

Figure 2: Thermal control for the human body.

radiant temperature and the dry bulb temperature is less than 5 degrees Celsius.

Air Velocity

Air movement is very effective in increasing heat loss from the body at high temperatures when sweating occurs. The air movement enhances the evaporation of sweat from the body thereby cooling down the body.

Air velocity of up to 0.1 metre per second may lead to a feeling of stuffiness indoors. Air velocities of 0.1 to 1.0 m/s are comfortable indoors when air movement is required but above this level there is discomfort. A kata thermometer (figure 3) is used to measure air movement due to low velocities.

Outdoors, wind speeds of up to 2.0 m/s can help achieve comfort, especially when the humidity is high. Wind speeds of over 5.0 m/s lead to considerable discomfort.

The Relative Humidity

When there is low humidity the air is very dry and sweating is more effective in cooling down the body. However, when the humidity is high the air is damp and clammy and sweating is no longer very effective in cooling down the body.

Thermal comfort can be achieved when the relative humidity is between 20 and 90%.

The Intrinsic Clothing

Clothing is measured in clo units:

0.5 clo => a pair of shorts for men and a cotton dress for women.

1.0 clo => normal business suit, shirt and underwear

2.0 clo => outdoor winter clothing.

The range of intrinsic clothing for thermal comfort is taken to be from 0.5 to 1.0 clo.

The Activity

The activity represents the metabolic rate. The higher the activity, the more heat is produced by the body. The metabolic rate is measured in W/m . The rate for a person sitting is about 58 W/m and this is taken as the basic unit of activity known as the "met".

As such:

Sitting = 1 met

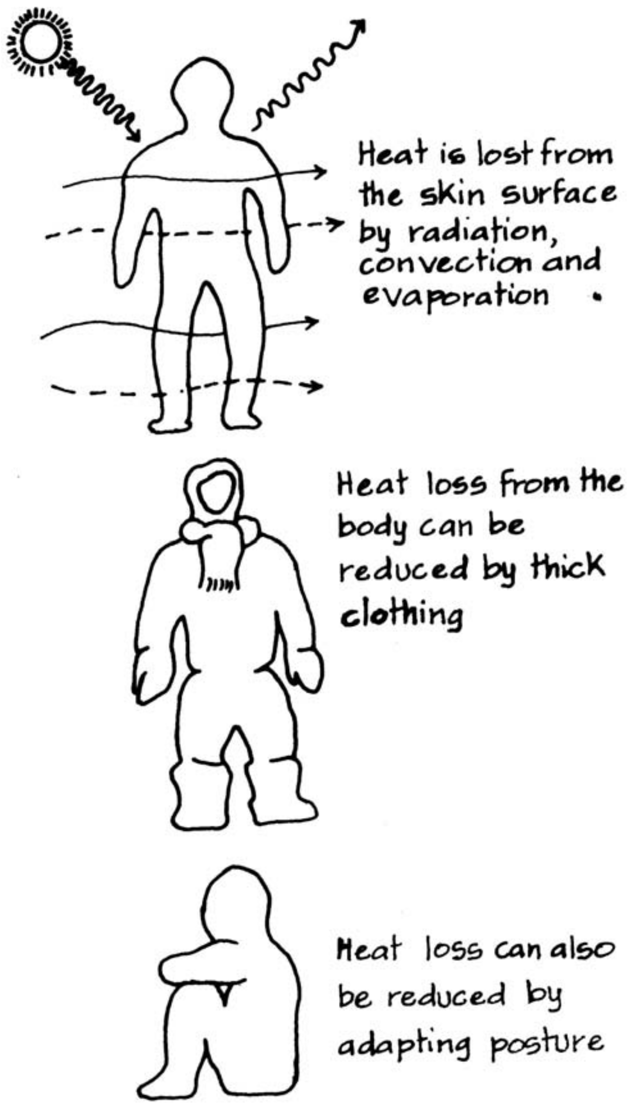

Figure 3: Thermal control for the human body.

Sleeping	=	0.7 met
Standing relaxed	=	1.2 met
Dancing	=	2.4 -4.4 met
Heavy machine work	=	3.5 -4.5 met

Comfort can be maintained with metabolic rates from about 0.7 to 2.5 met.

4. The Thermal Indices.

Need for a Thermal Index.

We have discussed how the six factors of air temperature, mean radiant temperature, air velocity, relative humidity, intrinsic clothing and level of activity affect thermal comfort. These factors were discussed separately but any assessment of thermal comfort for practical design purposes must take cognisance of all the six variables simultaneously. What is needed is a scale that will combine the effects of all these factors. Such a scale is called a thermal index or a comfort scale.

The search for a thermal comfort scale was a long and eventful one. Many concepts passed on to the archival pages of history as new advances were made, especially in medicine and thermometry. Arbuthnot established the first milestone in 1733 when he pointed out the chilling effects of wind by dispersing the layer of warm, moist air around the body. This was quickly followed by several developments as detailed by Markus and Morris(1980). The more salient points include the proposal of the Effective Temperature Index (ET) by Houghton and Yaglou in 1923 and the Corrected Effective Temperature Index (CET) proposed by Bedford in 1946. Other important concepts include the Equivalent Temperature (1929), the Operative Temperature and the Standard Effective Temperature.

Examples of Thermal Indices

The search for a thermal index resulted in the development of several thermal indices or scales. The most important are presented below:

The Standard Effective Temperature (SET).

This is a rational physiologically-based index of comfort. It expresses any environment, clothing and activity level in terms of a uniform

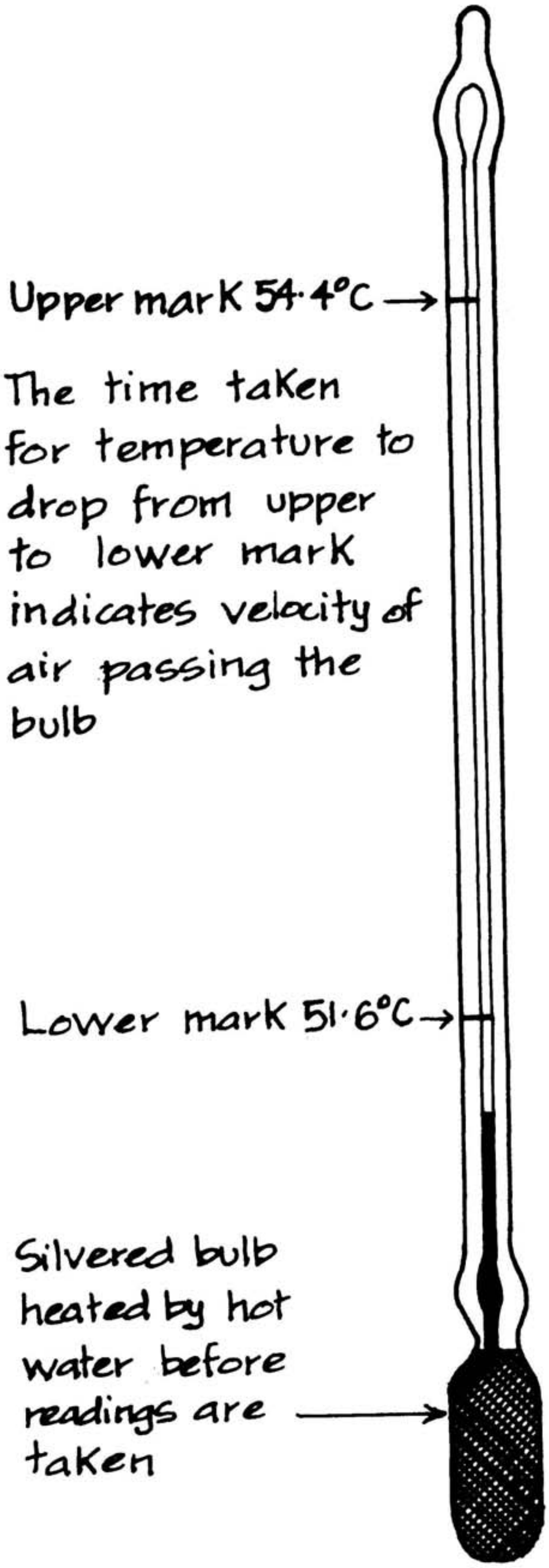

Figure 4: The kata thermometer.

environment standardised at 50 percent RH, air velocity of 0.125 m/s, activity of 1 met and intrinsic clothing at 0.6 clo. See figure 4.

Note that 0.125 m/s is the velocity of still air in a room, 1 met is equivalent to sedentary metabolic rate at 58 W/m^2 and zero external work. 0.6 clo is equivalent to normal, lightweight, indoor clothing.

Hence in order to determine SET the following variables should be known: the relative humidity, the air temperature, the mean radiant temperature, the air velocity, the intrinsic clothing and the activity.

The Effective Temperature (ET).

This is the temperature of a still, saturated atmosphere, which would, in the absence of radiation, produce the same effect as the atmosphere in question. ET was developed in 1923 by Hougton and Yaglou while working for ASHRAE. See figure 5.

It combines the effects of the following:

the relative humidity

the air velocity

the air temperature.

The Corrected Effective Temperature.

This scale is an improvement on the ET scale as it considers radiation effects as a fourth determinant of comfort.

The Use Of The Effective Temperature Nomogram

The most widely used thermal index is the Effective Temperature Index (ET). The Effective Temperature nomogram can be used to determine the Effective Temperature given:

the dry bulb or globe temperature

the wet bulb temperature

the air velocity.

To find the Effective Temperature for a given set of conditions:

the globe or air temperature is marked on the scale on the left hand side of the nomogram.

the wet bulb temperature is marked on the scale on the right hand side of the nomogram.

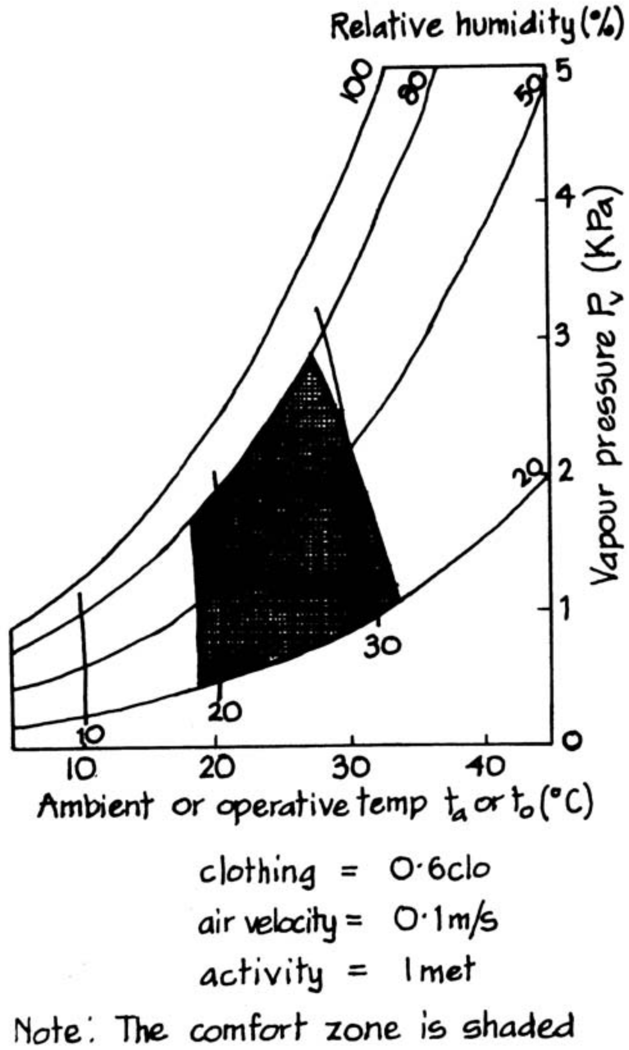

Figure 5: Thermal comfort chart for the Standard Effective Temperature index.

These two points are joined by a line.

The point of intersection of this line and the line representing the appropriate air velocity is determined.

The Effective Temperature is then read.

After the effective temperature has been determined it is necessary to compare this value with the comfort limits. There is no agreement as to the lower and upper comfort limits but the values commonly used for tropical countries are as follow:

lower limit: 22 degrees Celsius

optimum temperature: 25 degrees Celsius

upper limit: 27 degrees Celsius

However, recent research by Ogunsote (1988) indicates that comfort limits valid for Nigeria are 20-25 degrees Celsius.

For example, given a wet-bulb temperature of 25 degrees Celsius and a dry-bulb temperature of 20 degrees Celsius, the Effective Temperature with air movement of 1 m/s is about 21.5 degrees Celsius.

The same nomogram is used for both Effective and Corrected Effective Temperatures. The only difference is that the air temperature is used to obtain the Effective Temperature while the globe temperature is used for the Corrected Effective Temperature.

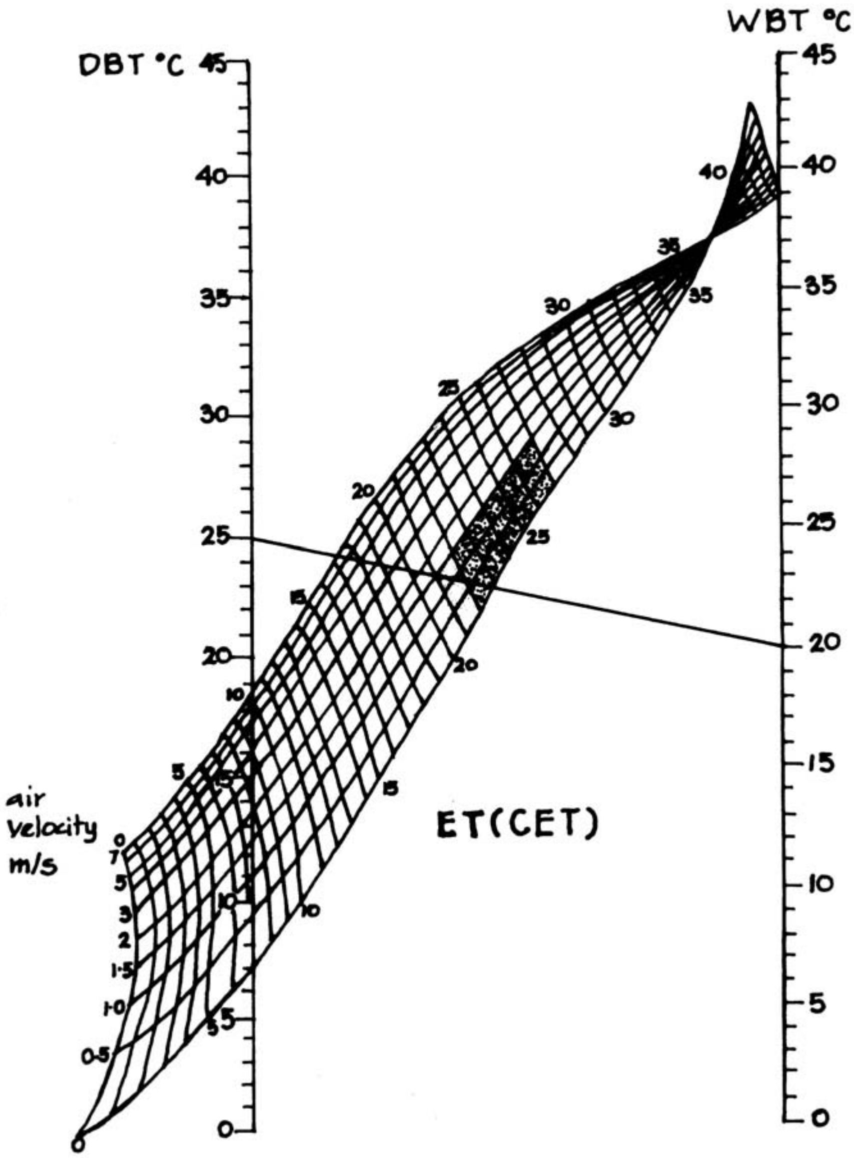

Figure 6: Effective Temperature nomogram for persons wearing normal clothes.

The Resultant Temperature (RT).

The Resultant Temperature is an improvement on the ET and the nomograms defining them are almost identical. It was developed in France by Missenard and is considered unreliable for tropical conditions as it does not sufficiently incorporate the cooling effects of air movement over 35 degrees Celsius and 80 percent RH. See figure 6.

The Heat Stress Index (HSI).

The Heat Stress Iindex, which is reliable between 27 and 35 degrees Celsius, 30 and 80 percent RH, takes the metabolic heat production of subjects doing various kinds of work as an indication of heat stress.

The Equivalent Warmth (EW).

This scale was developed by Bedford in England and is based on the reaction of 2000 factory workers engaged in light work, under varying indoor conditions. It takes into account the air temperature, the RH and the mean radiant temperature. The EW is reliable within the comfort zone up to 35 degrees Celsius with low RH and up to 30 degrees Celsius with high RH. It however under-estimates the cooling effect of air movement at high humidities.

The Equatorial Comfort Index (ECI).

This scale, which is similar to the ET, was developed by Webb in Singapore and it accommodates the effects of temperature, humidity and air movement.

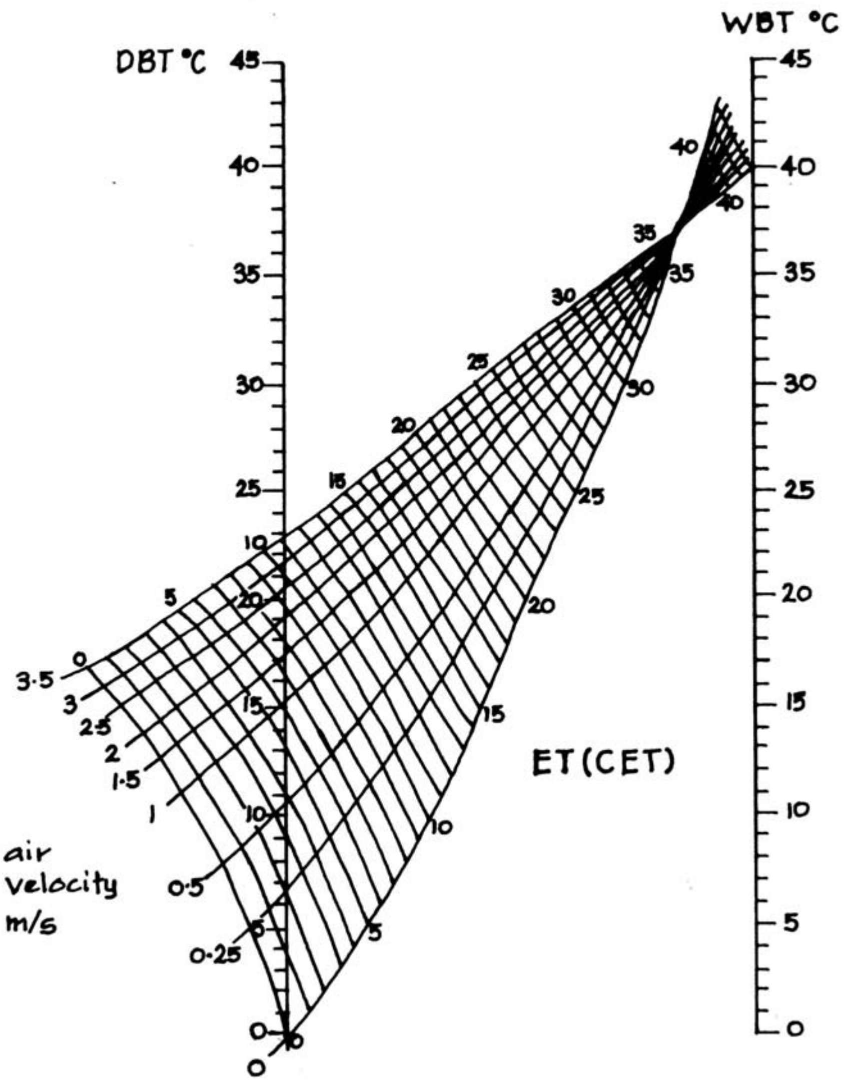

Figure 6: Effective Temperature nomogram for persons stripped to the waist.

The Predicted Four Hour Sweat Rate (P4SR).

British naval authorities developed the P4SR to consider the special heat stresses experienced by seamen, which is indicated by the rate of sweat secretion from the body, the pulse and the internal temperature. It is considered unsuitable for temperatures below 28 degrees Celsius and it underestimates the cooling effects of air movement at high humidities. The effects of air temperature, the humidity, the air movement, the metabolic rate, the clothing and the mean radiant temperature of the surroundings are considered.

The Operative Temperature (OT).

Defined as the uniform temperature of an imaginary enclosure in which man will exchange the same dry heat by radiation and convection as in the actual environment, the OT combines the effects of radiation and air temperature. It was developed by Winslow, Herrington and Gagge, and is similar to the EW. See figure 7.

The Index Of Thermal Stress (ITS).

This is the calculated cooling rate produced by sweating which would maintain the thermal balance under the given conditions as established from first principles by Givoni (1976). It is reliable in the range of conditions between comfort and severe stress, provided that thermal equilibrium can be maintained.

The Bioclimatic Chart.

Victor Olgyay's conviction that there is no point in defining a single-figure index, as each of the components are controllable by different means resulted in the construction of the bioclimatic chart. The comfort zone is defined in terms of the dry bulb temperature and the RH, and the effects of air movements and radiation on the comfort zone are indicated. See figure 8.

Use of the Bioclimatic Chart.

The bioclimatic chart is popular mainly because of its simplicity of use and the ease with which results can be interpreted for design purposes. For very simple analysis, the average monthly air temperatures and relative humidities may be used. The use of the minima and maxima of these climatic variables is however more informative and this is the procedure described here.

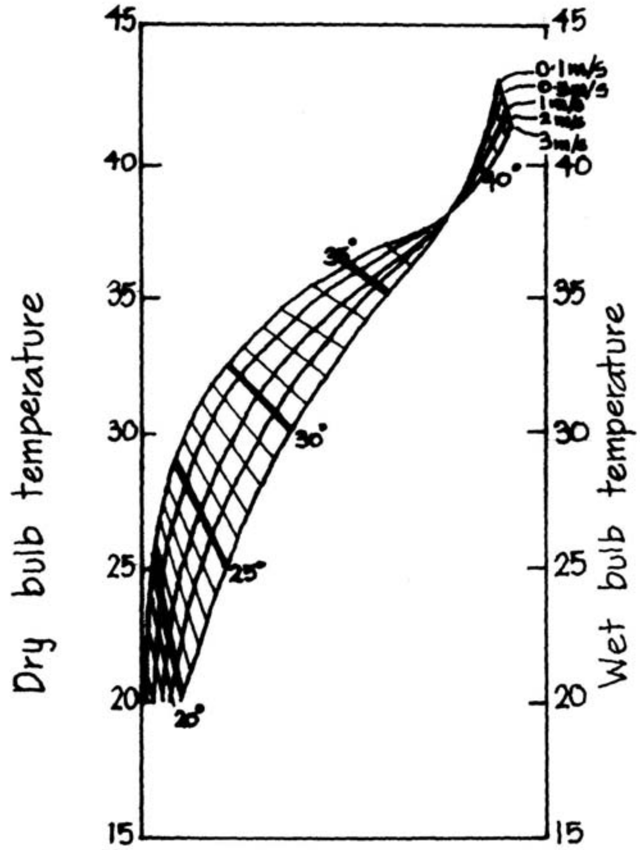

Figure x: Chart of the Resultant Temperature index.

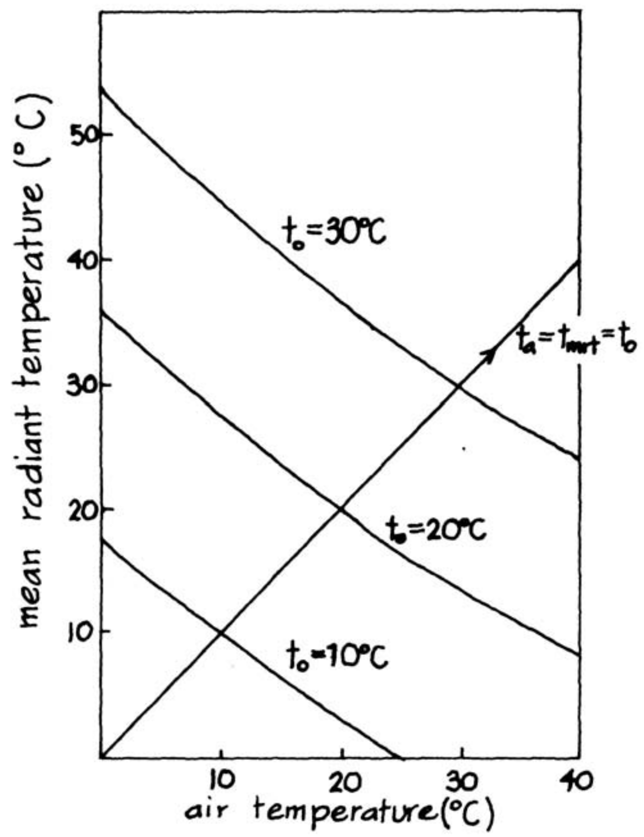

Figure x: Operative Temperature chart. Air velocity = 0.1 m/s and activity = 1 met.

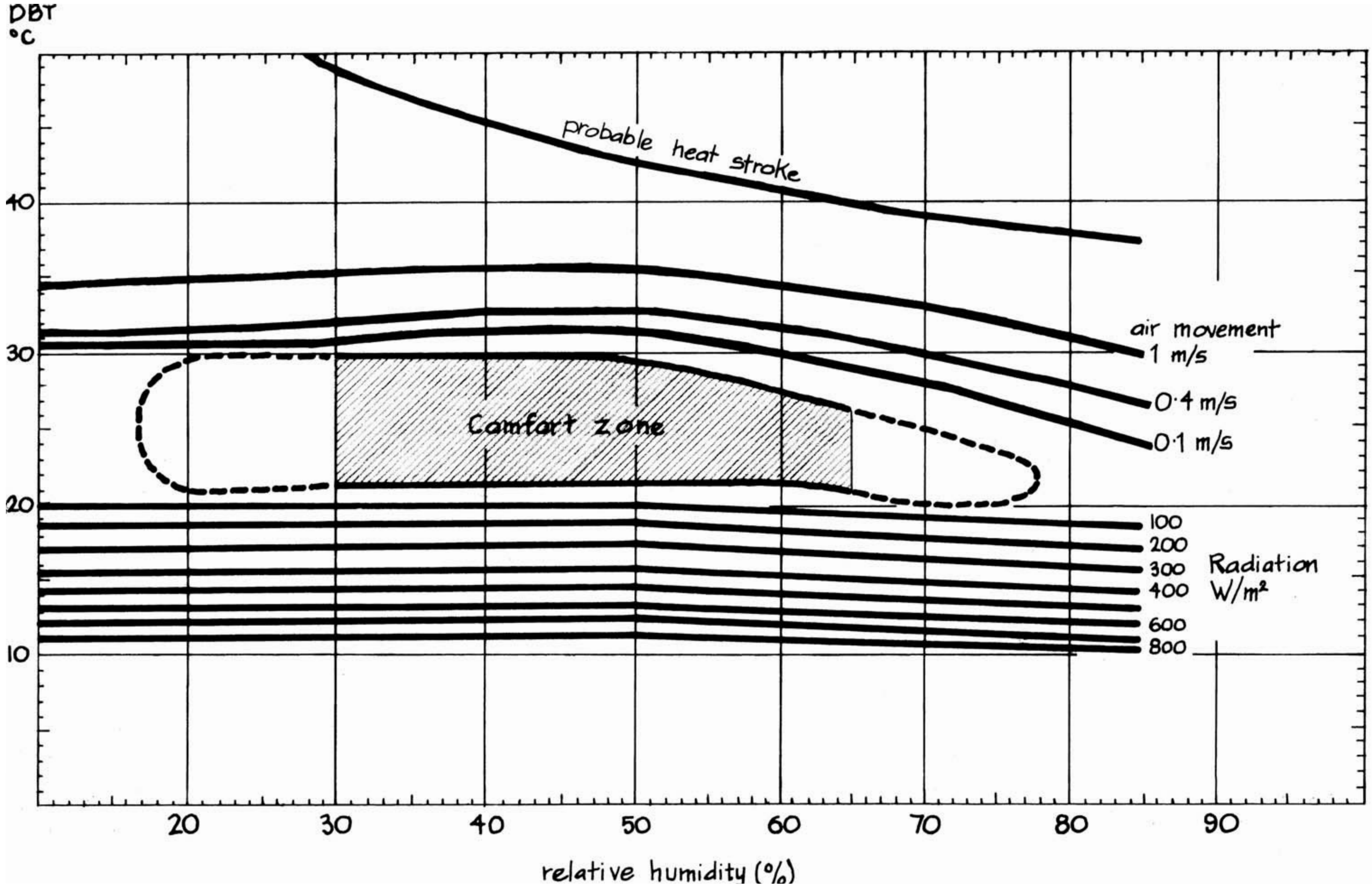

Figure x: The bioclimatic chart.

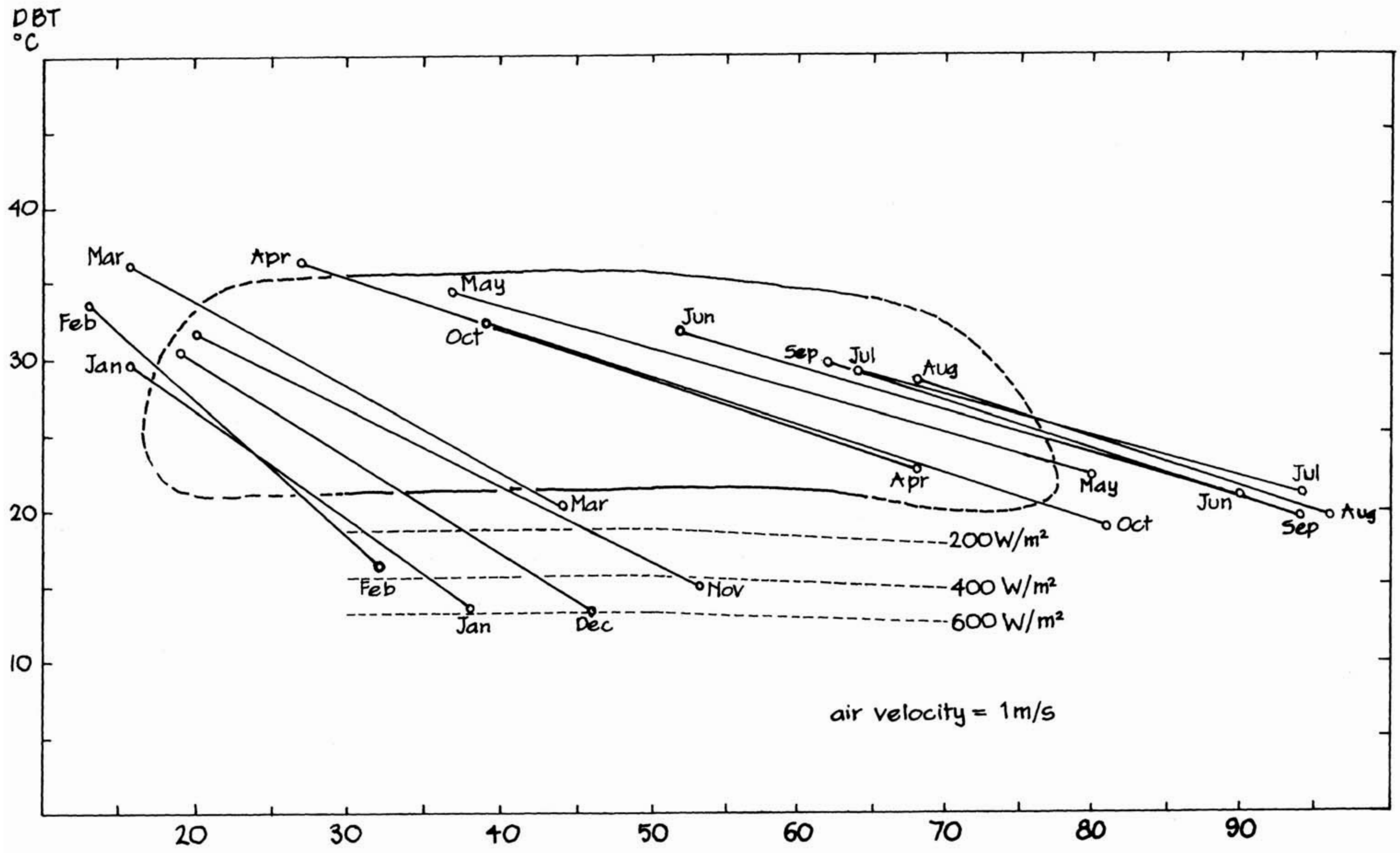

Figure x: Example of the use of the bioclimatic chart for Zaria.

The monthly minima and maxima of air temperature and relative humidity are usually readily available data and are sufficient for this analysis. However, it is advisable to obtain the average monthly wind velocity and mean monthly solar radiation. A reduction factor should be used to convert the wind velocity to air movement at the level of the human body. See table 3.

Take the monthly mean minimum temperature and the monthly mean maximum relative humidity for January. These two variables define a point on the Bioclimatic Chart. Take the monthly mean maximum temperature and the monthly mean minimum relative humidity for the same month of January and use this to define a second point. See figure 9. Join these two points together with a straight line. Use the wind velocity and the solar radiation for the same month to determine whether there is hot discomfort, cold discomfort or comfort for the two points. You may indicate the thermal stress thus ascertained symbolically. Repeat the process for the remaining eleven months of the year. This chart gives an indication of the duration and nature of thermal stress throughout the year and design decisions can be made on this basis.

Table 1: Comfort limits proposed by Mahoney.

Scale conditions		Comfort limits C	
AMT	Humidity (%)	Day	Night
Over 20 C	0 - 30	26 - 34	17 - 25
	30 - 50	25 - 31	17 - 24
	50 - 70	23 - 29	17 - 23
	70 - 100	22 - 27	17 - 21
15 - 20 C	0 - 30	23 - 32	14 - 23
	30 - 50	22 - 30	14 - 22
	50 - 70	21 - 28	14 - 21
	70 - 100	20 - 25	14 - 20
Under 15 C	0 - 30	21 - 30	12 - 21
	30 - 50	20 - 27	12 - 20
	50 - 70	19 - 26	12 - 19
	70 - 100	18 - 24	12 - 18

The Mahoney Scale.

For design purposes it is sometimes enough to be able to determine hot or cold discomfort for each month of the year. Carl Mahoney proposed a scale which is capable of doing this on the basis of only relative humidity and temperature data. The scale differentiates between day and night comfort limits with lower limits for the night since people generally tolerate lower temperatures in the night. There are different limits for hot, average and cold climates, and these are presented in table 1.

The Evans Scale.

The comfort limits for climatic

Table 2: Comfort temperature ranges according to Evans.

Scale	Conditions	Humidity (%)	Day temp. C	Night temp. C
A	Upper range of comfort with 1m/sec air movement	0 - 30	32.5 - 29.5	29.5 - 27.5
		30 - 50	30.5 - 28.5	29 - 26.5
		50 - 70	29.5 - 27.5	28.5 - 26
		70 - 100	29 - 26	28 - 25.5
B	Range of comfort with light summer clothes or blanket at night	0 - 30	30 - 22.5	27.5 - 20
		30 - 50	28.5 - 22.5	26.5 - 20
		50 - 70	27.5 - 22.5	26 - 20
		70 - 100	27 - 22.5	25.5 - 20
C	Lower range of comfort with normal of warm clothes and thick bedding at night	0 - 30	22.5 - 18	20 - 16
		30 - 50	22.5 - 18	20 - 16
		50 - 70	22.5 - 18	20 - 16
		70 - 100	22.5 - 18	20 - 16

design proposed by Martin Evans are very similar to the ones proposed by Carl Mahoney. See table 2. The limits are for hot, "comfortable" and cold climates. Evans also recognizes that there are various combinations of climatic variables which produce conditions under which natural means are not sufficient for the attainment of comfort and mechanical aids are needed. These conditions are shown in table 3.

5. Applicability of the Indices.

The choice of a thermal index for climatic analysis is closely related to the purpose of the analysis, the availability of data and the simplicity of the particular thermal index. Also of importance is the range of application of the particular index. Nomograms, where necessary, should of course be available. For student projects the Bioclimatic Chart, the Effective Temperature, the Standard Effective Temperature, the Mahoney Scale or the Evans Scale are commonly used. It should be noted that there may be slight variations in the comfort limits proposed by these indices and those actually applicable in the Nigerian climate. For extensive analyses the use of a computer program such as COLDHOT is advisable.

Table 3: Temperature and humidity limits for different forms of discomfort.

Condition	Mean daily temp. (C)	Mean daily humidity	Diurnal range
High temperature and high humidity by day	over 27	over 70%	-
	over 27.5	50 - 70%	?10 C
High temperature and high diurnal range	over 32.5	0 - 30%	-
	over 30.5	30 - 50%	-
	over 29.5	50 - 70%	>10 C
Excessive discomfort	over 38	0 - 30%	-
	over 37	30 - 50%	-
	over 35.5	50 - 70	>10 C
	over 32	over 70%	?10 C
Day and night comfort but with high diurnal range	10 - 32.5	0 - 30%	>10 C
	10 - 30.5	30 - 50%	>10 C
	10 - 29.5	50 - 70%	>10 C
	10 - 29	over 70%	>10 C
Low day temperatures	15 - 18 (fresh)	-	-
	10 - 15 (cool)	-	-
	below 10 (cool)	-	-
Day comfort	all conditions not included above		
High temperature and high humidity by night	above 25.5	above 70%	
	above 26	50 - 70%	?10 C
High temperature and low humidity by night	above 27.5	0 - 30%	-
	above 26.5	30 - 50%	-
	above 26	50 - 70%	>10 C
Low night temperatures	below 10	-	-

6. Tests and Exercises

1. Explain how the human body maintains its thermal balance.

2. What are the factors that affect thermal comfort? Explain how these factors affect the sensation of comfort and state the limits within which comfort can be achieved.

3. Explain the effect of the following factors on human comfort:

   a. Air temperature

   b. Humidity

   c. Wind

4. Describe ten indices of thermal comfort and relate their applicability to the Nigerian climate.

5. Explain the importance of thermal indices in design with climate.

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