1 WHY IT IS IMPORTANT

1.1 User satisfaction

In surveys of user satisfaction in buildings with passive solar features, Griffiths found that having the `right temperature' was one of the things people considered most important in a building. This is a result which is borne out by many other surveys over the years. Griffiths also found that `air freshness' was an important requirement mentioned by the respondents to his survey. The subjective feeling of the freshness of the air was found by Croome to be closely related to temperature of the air. Thus two important features in the user satisfaction with a building are closely related to temperature.

At the same time dissatisfaction with the thermal environment is widespread, even in buildings with sophisticated controls. Complaints of overheating in winter and coldness in air-conditioned buildings in summertime are commonplace. A recent survey in an air-conditioned buildings in Sydney found up to 80% of occupants found the building thermally unsatisfactory.

Dissatisfaction can also cause people to 'take the law unto their own hands' and find ways to make themselves comfortable – an electric heater or comfort cooler for instance – and this will increase energy use.

1.2 Energy consumption

The indoor temperature set for a building in the heating or cooling season is an important factor in deciding the energy used by the building. The heat loss from, or gain by, the building is proportional to the indoor-outdoor temperature difference. One method used to assess heating requirements for buildings is to find, from weather data, the number of `degree-days' in the heating season. This is found by multiplying the days during which there is an indoor-outdoor temperature drop by the number of degrees temperature drop for each day.

In the UK, for instance, the design degree-days for base indoor temperature of 18.0°C is about 2000, for base 15.5°C it is about 1500. These figures imply a decrease of 25% in heating energy use for an internal temperature change of 2.5K or 10% per K. This saving includes contributions from the change in the indoor-outdoor temperature difference and the decrease in the heating season: a lower indoor temperature means that the heating does not need to be turned on so early in the year, and can be turned off at an earlier date. In addition to the heat consumption considerations another factor which is affected by the design indoor temperature is the sizing of the heating or cooling equipment.

Similar considerations clearly apply to an air-conditioned building: a decrease in the outdoor-indoor temperature difference will decrease the cooling load. There are two factors which make the reduction of cooling loads for air
conditioning an area of critical concern. Firstly air conditioning uses electrical power which is generally highly inefficient in its generation, and consequently wastes large amounts of energy in the cooling of buildings. Secondly many of the problems giving rise to the need for air conditioning can be simply solved by increasing the thermal performance of the building envelope.

2 THE UNDERLYING PROCESSES

The thermal interaction between man and the environment is highly complex and has been the subject of a great deal of study. The internal processes by which we produce and respond to heat have been studied by physiologists, our conscious feelings about the environment by psychologists and the processes of heat transfer between man and environment by physicists. In addition there are social factors which determine the way we react to the environment which is the realm of the social sciences while it is the role of environmental engineers decide how our needs can be satisfied in buildings. The study of thermal comfort therefore has to take all these considerations into account.

We are not concerned here with a detailed investigation into the phenomena underlying thermal comfort, which have been adequately described elsewhere but it is useful to briefly touch on the main points.

2.1 Physiology

We produce energy by metabolising food and most of this energy takes the form of heat. This `metabolic heat' is produced by the body all the time, though more is produced when we are active, and the more active we are the more heat is produced. Muscular activity is particularly associated with heat production, though all bodily functions produce some heat. Heat is transported around the body by the blood. To balance the metabolic input, heat is continually lost to the environment through the skin and through the surfaces of the lungs.

For the proper functioning of the organs of the body, and particularly for that of the brain, the temperature of the internal organs (the `deep-body' or `core' temperature) must be maintained constant. The seat of the controlling mechanism is the brain. If our brain temperature falls outside these very close limits, the body will react physiologically to restore heat balance.

If the core temperature drops the brain then initiates vaso-constriction. This is the process by which blood circulation to the peripheral parts of the body (most noticeably the hands and feet) is reduced, thus reducing the supply of heat and causing the temperature of the skin to drop. This cuts the heat loss to the surroundings. A further drop in core temperature leads first to an increase in the tension in the muscles and then to shivering so increasing metabolic heat production.

If the core temperature rises the first line of defence is vaso-dilation, here the blood supply to the periphery is increased, flushing the skin with blood and
increasing skin temperature and heat loss to the surroundings. Further
increases in core temperature give rise to sweating. This increases heat loss by
evaporation of water from the surface of the skin. Much of the work done by
physiologists has been concerned with the limits of human endurance in heat
and cold. In buildings we are generally interested in the physiology of moderate
heat stress.

2.2 Psychophysics

The unconscious thermoregulatory actions controlled from the brain are
augmented by the thermal sense in the skin. This adds information about the
skin temperature, warning of conditions which might pose a danger.

Our impression of the warmth or cold of our environment arises in part from
the skin sensors. It is integrated with the core temperature so that the overall
sensation may be pleasing or displeasing depending on whether the overall
effect is towards or away from the restoration of deep body equilibrium. Thus a
cold sensation will be pleasing when the body is overheated, unpleasant if the
core is already cold. At the same time, the temperature of the skin is by no
means uniform. As well as variations caused by vasoregulation there are
variations in different parts of the body which reflect the differences in
vasculation and sub-cutaneous fat. The wearing of clothes also has a marked
effect on the level and distribution of skin temperature, as might be expected.
So sensation from any particular part of the skin will depend on time, location
and clothing as well as the temperature of the surroundings.

Psychophysics is the study of the relation between our sensations and stimulus
we receive from the physical world. The science of psychophysics has been
concerned with investigating the relationship between sensations such as
apparent brightness and stimulus of measured light level or the sensation of
loudness and the stimulus of sound level. The thinking behind many field
studies of thermal comfort has been that of psychophysics: relating the overall
thermal sensation to the stimuli of the thermal environment (see chapter 3).

However an ability to say how we feel does not imply a one-to-one relationship
between comfort and the physical conditions underlying it. Just as we have
shown that the pleasure given by a thermal stimulus depends on the
physiological conditions against which the stimulus is received, so there is an
uncertainty about our thermal sensation not just in the physiology but in the
social and other conditions prevailing. Thus we are unable to say that such-
and-such a set of conditions will give rise to such-and-such a sensation, only
that there is a probability that it will.

2.3 Physics

To the physicist the human being is a heated body with variable surface
characteristics, losing heat to the environment through three principal
pathways, Convection, radiation and evaporation. In certain circumstances
significant amounts of heat are also lost by conduction to surfaces we are in contact with, but this is normally a secondary path of heat loss.

2.3.1 Convection

We are surrounded by air with which we exchange heat. Where the temperature of the air is below mean skin temperature then there will be a net heat loss from the body by convection. Where the air temperature is above skin temperature then we will gain heat from it. The heat is then carried away by the movement of the air in contact with us. In cool, still conditions air movement around the body will be caused by the air, heated by the body, rising up over the it and forming a `plume' above the head and then dispersing. Any additional air movement will add to the cooling by helping to strip the warmed air from the body at a greater rate, effectively cooling the air in contact with the body. Since we are talking here of the air movement relative to the body surface, activities such as walking will add to the effective air movement. Turbulence in the air stream also has an effect helping to increase the cooling effect of air movement.

These effects will occur whether or not the body is clothed. Where clothing is worn the cooling effect of convection occurs at the clothing surface. The overall effect is to increase the temperature difference across the layer of clothing thereby cooling the skin `at one remove'. With noticeable air movement the nature of the clothing will have some impact on its effectiveness as an insulator: a permeable material allowing the cool air to penetrate further and reduce the garment's effectiveness as an insulator.

Where the air in contact with the body is hotter than skin temperature all these effects act in the opposite direction to heat the body.

In conclusion the cooling (or heating) effect of the air depends on the difference between air temperature and skin (or clothing surface) temperature and of the air movement. The effect of air movement is generally considered to be roughly proportional to the square root of the air velocity.

2.3.2 Radiation

All bodies emit radiant heat at their surface. At the same time surrounding surfaces are radiating to the body in a similar fashion. So a balance is set up whereby the body will loose heat if the surroundings are colder and gain heat if they are hotter. If the surroundings were all at one temperature the situation would be relatively simple. But of course they are not, in any real situation there will be cold windows or hot ceilings, radiators and even the sun. There is not space here to go too far into the details of radiant energy exchange. Radiant heat loss is roughly proportional to the temperature difference between the clothed surface and the surroundings.

2.3.3 Evaporation
When water evaporates it extracts a quantity of heat (the latent heat of evaporation) from its surroundings. The evaporation of water from the surface of the skin means most of the latent heat is extracted from the skin and cools it. This cooling effect is very powerful, (the evaporation of 1g/minute is equivalent to 41W) and is used by the body to cool us when we sweat. It is not the sweating that cools us but the evaporation of the sweat from the skin.

It is as well to remember that the total heat lost by evaporation is determined by the amount of sweat produced and not the maximum that can be evaporated (this would require the body to be totally wet with sweat). So the heat loss by evaporation is essentially determined by the thermoregulatory system and not the physical conditions. Air movement tends to increase evaporation in much the same way as it increases convective heat loss. Skin wettedness will affect the thermal balance when it implies that the body is having trouble evaporating all the sweat it is producing (though discomfort caused by sweaty skin may also be a problem).

There is also some residual heat loss by evaporation even when sweating is not necessary. This is due to evaporation from the surface of the lungs during breathing and through the evaporation of insensible moisture on the skin. The rate of heat loss from the lungs depends on metabolic rate (because the rate of breathing depends on metabolic rate) and the difference between the saturated water vapour pressure at core temperature (in effect almost a constant) and $p_a$, the loss from the skin depends on $(p_{sk} - p_a)$ in much the same way as sweating. These contributions to heat loss can be a substantial part of the whole, (quoted as 20-30% for a sedentary person in thermal comfort) - particularly so in cool or dry conditions.

### 2.3.4 Clothing

Clothing plays a major role in enabling man to survive outside the tropics where temperatures are typically closer to body temperatures than in other regions. In the physical model of the heat transfer the clothing is assumed to be a uniform layer of insulation between the body and the environment with a single surface temperature. Quite clearly this is an approximate treatment, since the clothing is anything but uniform. The face in particular is generally unprotected and the actual clothing insulation varies from place to place on the body according to the nature of the clothing ensemble. In practice, however, the assumption appears to work quite well, and the overall insulation of the clothing can be expressed as the sum of the contributions from the individual items of clothing being worn, as if they were each spread over the whole of the body surface. In this context the layers of air trapped between multiple layers of clothing and between the clothing and the skin are counted as part of the ensemble.

The insulation of the clothing is generally expressed in `clo units`. The clo unit was introduced to facilitate the visualisation of clothing level, and is the insulation necessary to keep a person comfortable at 21°C - about that of an office worker's suit. In addition to acting as insulation against the transfer of
dry heat, the clothing has an effect on the heat loss by evaporation. Firstly the
clothing affects evaporative cooling by introducing extra resistance to the
diffusion of water vapour away from the skin. The strength of this effect
depends on the nature of the clothing and its permeability to moisture. The
second way clothing effects evaporative cooling is that it absorbs excess
moisture next to the skin. The absorbed moisture is then evaporated from the
clothing and not from the skin, so that the latent heat is removed from the
clothing and is not so effective in cooling the skin.

The actual way in which clothing works is often far more complex than the
classic model outlined above. In some hot dry climates, for instance, the
inhabitants wear loose, multiple layered clothing. The function of the clothing
is then to keep the high environmental temperatures away from the skin, whilst
allowing heat loss by evaporation when dry air is pumped through the clothing
as the body moves. Where there is a high rate of sweating the heat loss can
actually be increased by the clothing, by providing extra surfaces from which
evaporation can take place and cooling the space between the skin and the
inner layer of clothing.

Another complication in dealing with clothing is that its function is not purely
thermal. The way in which we use clothes is determined by our social as well as
our thermal needs. Such variations as wearing a jacket open or closed can
make a significant difference to its thermal characteristics. Fanger and Wyon
have suggested that chair upholstery may contribute as much as 0.2- 0.4clo, a
fact not included in any of the standard methods for estimating clothing
insulation. The need to specify the value of the clothing insulation and
permeability is a source of considerable uncertainty in the physical model of
human heat exchange.

2.4 Behaviour

Before we introduce the various approaches to thermal comfort studies in
chapter 3 it is worth noting that behaviour plays an important role in our
thermal interaction with the environment. All the approaches to our thermal
interactions with the environment listed above have in effect assumed that we
are acted upon by the environment and react to it in a largely passive way. In
fact there is a very active interaction between man and the environment.
Thermal interactions take two major forms:

- actions which change the temperature which we find comfortable (such
  as chages in clothing, posture or metabolic rate) so as to suit the
  prevailing conditions (see figure 2.1)
- actions which change the environment to match the comfort
  temperature of the occupants (see figure 2.2)

These interactions are generally under conscious control and augment the
unconscious physiological reactions which have been referred to.
Time also plays a part in this interaction. There are four typical time-periods for these effects:

- Instantaneous - the change of clothing in anticipation of a thermal change such as putting on a coat before going out.
- Within-day - the clothing changes, changes of posture or environmental adjustments we use to cope with unexpected environments on a particular day.
- Day-to-day - we learn from one day to the next how to cope with changing conditions such as the weather.
- Longer term - seasonal changes in clothing, use of buildings, activities learnt over a longer period.

In order to fully describe people's thermal experience we need to take account of all these changes. The total picture should be consistent with the findings drawn from physics and physiology, but it will change with climate, place and time in a dynamic and interactive way.

3 EXISTING METHODS OF SETTING THERMAL STANDARDS

Before the existence of controllable heating and ventilation the design of the thermal environment was largely down to the designer's experience. The number of fireplaces to provide in a building, the way in which the rooms were shaded and ventilated were part of the learning which was passed from builder to builder, successful solutions hopefully becoming the norm. With the advent of modern air-handling and central heating systems the question of what conditions the system should be aiming to provide became crucial.

One approach to finding what conditions are comfortable is to conduct surveys in the field. Conditions are left to vary as they will and the subjects to dress and behave as they would normally do. The experimenter then measures the physical characteristics of the environment and relates these to the subjects' feeling of warmth to find the relationship.

Experimental work can also be carried out in a climate chamber. Climate chambers are in effect laboratories which enable the experimenter to adjust the environmental conditions with regard to air and radiant temperature, humidity and air velocity. Such chambers have been widely used in controlled experiments investigating the effect of physical parameters on comfort. This approach treats each component of the man-environment interaction separately.

These two approaches can be called the empirical and the analytical.

3.1 Empirical field surveys

In the field survey the method is to ask subjects taking part in the survey to assess their thermal sensation on a subjective scale running from `too cold' to `too hot'(see below). This assessment is generally known as the `Comfort
Vote'. The environmental variables are measured at the same time as the subjective reactions are taken. The researcher in such surveys has often been a local person, or someone with an interest in that particular climate. The interest is generally in finding a temperature or a range of temperatures and other environmental variables which people in that locality will find comfortable. Because the aim is to obtain a typical reaction to conditions there is no attempt to interfere with normal conditions or modes of dress, so the full complexity of the situation is included in the responses of the subjects.

**COMFORT VOTES**

The subjective sensation of warmth, or thermal comfort, of the subject has traditionally been measured using a seven-point scale. The subject is asked to rate his or her feelings on a descriptive scale such as the ASHRAE or the Bedford scales:

<table>
<thead>
<tr>
<th>ASHRAE</th>
<th>Bedford</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hot</td>
<td>+3</td>
</tr>
<tr>
<td>Warm</td>
<td>+2</td>
</tr>
<tr>
<td>Slightly warm</td>
<td>+1</td>
</tr>
<tr>
<td>Neutral</td>
<td>0</td>
</tr>
<tr>
<td>Slightly cool</td>
<td>-1</td>
</tr>
<tr>
<td>Cool</td>
<td>-2</td>
</tr>
<tr>
<td>Cold</td>
<td>-3</td>
</tr>
</tbody>
</table>

Much too warm  Too warm  Comfortably warm  Comfortable neither warm nor cool  Comfortably cool  Too cool  Much too cool

The resulting number is called the Comfort Vote (C).

The first aim is to discover what combination of environmental variables best describes the subjective responses of the subjects. To do this the researcher performs a statistical analysis of the data. A number of such `comfort indices' have been put forward over the years. Another type of analysis enables the proportion of people comfortable at any particular temperature (or combination of variables) to be calculated. The results obtained from any particular survey are specific to the survey, i.e. to that group of subjects in the environment encountered. The effect of experience, environment and climate as well as the social milieu are all part of the subjects' response.

The underlying assumption of the field survey is that people are able to act as meters of their environment. This assumption is rooted in the findings of psychophysics. In effect the subject is used as a comfort meter, not of temperature alone but of all the environmental and social variables simultaneously. The results obtained from such surveys are very specific to the conditions measured. This means that any formula resulting from the statistical process must be treated with extreme caution, and any such formula should be judged on physical as well as statistical grounds.

Nevertheless the field survey is the key to understanding thermal comfort. Any theoretical model which does not explain the results of measurements in the
field among real people cannot be trusted to set standards which will have meaning among those same real people.
In order for the field results to have general applicability we have to produce general rules from the individual results. This is the basis upon which we can move forward.

3.2 Analytical Approaches

There is an obvious advantage to having a complete picture of the various thermal factors involved in man's interactions with the environment. A number of workers have set out to build models of the physical and physiological conditions governing thermal comfort, the best known are those of Fanger's (1970) Predicted Mean Vote (PMV). Fanger's model forms the basis for the international ISO Standard 7730.

Fanger's basic premise is that a balance between the heat produced by the body and the heat lost from it is a necessary, but not a sufficient condition for thermal comfort. It is not sufficient because one can imagine situations in which a theoretical balance would occur, but which would not be considered comfortable. So the determination of comfort conditions is in two stages: first find the conditions for thermal balance and then determine which of the conditions so defined are consistent with comfort.

Fanger proposed that the condition for thermal comfort for a given person is that his skin temperature and sweat secretion must lie within narrow limits. Fanger obtained data from climate chamber experiments, in which sweat rate and skin temperature were measured on people at various metabolic rates who considered themselves comfortable, Fanger proposed that optimal conditions for thermal comfort were expressed by the regression line of skin temperature and sweat rate on metabolic rate from data in these experiments. In this way an expression for optimal thermal comfort can be deduced from the metabolic rate, clothing insulation and environmental conditions.

The final equation for optimal thermal comfort is fairly complex and need not concern us here. Fanger has solved the equations by computer and presented the results in the form of diagrams from which optimal comfort conditions can be read given a knowledge of metabolic rate and clothing insulation.

3.2.1 Predicted mean vote (PMV) and Predicted percentage dissatisfied (PPD).

Fanger extended the usefulness of his work by proposing a method by which the actual thermal sensation could be predicted. His assumption for this was that the sensation experienced by a person was a function of the physiological strain imposed on him by the environment. He calculated this extra load for people involved in climate chamber experiments and plotted their comfort vote against it. Thus he was able to predict what comfort vote would arise from a given set of environmental conditions for a given clothing insulation and metabolic rate.
Fanger realised that the vote predicted was only the mean value to be expected from a group of people, and he extended the PMV to predict the proportion of any population who will be dissatisfied with the environment. A person's dissatisfaction was defined in terms of their comfort vote. PPD is defined by Fanger in terms of the PMV, and adds information about the interaction between people and their environment to that already available in PMV. The distribution of PPD is based on observations from climate chamber experiments and not from field measurements.

### 3.3 Problems with the analytical approach.

We have deliberately avoided a detailed description of the Fanger PMV because of a wish to keep this discussion simple. There are however a number of points which need to be noted.

- the subjective data on which Fanger's model is based were obtained exclusively from climate chamber studies and in conditions where a steady state had been reached.
- prediction of conditions for optimal comfort, PMV or PPD require a knowledge of the clothing insulation and the metabolic rate
- value of clothing insulation used is obtained by the practitioner from tables in which clothing insulation is listed against descriptions of items or ensembles of clothing. The values of clothing insulation have been determined in experiments using heated manikins (see appendix C).
- metabolic rate is similarly obtained from tables of activities for which the appropriate metabolic rate is given (see appendix D).
- For the environmental designer these characteristics of the Fanger model pose a number of problems.
- He must know what clothing the occupants of the building will wear.
- He must know what activity they will be engaged in and there is an additional problem for buildings where a number of activities are taking place in the same space.
- He must assume that conditions in the building approach those of the steady-state in the climate chamber.

All these factors will influence the designer towards a highly serviced building producing closely controlled internal conditions appropriate to some assumed clothing norm and activity.

Such considerations render the method very difficult to apply to buildings with no mechanical heating and ventilation. The temperature in a free-running building will almost certainly change continually with time, particularly if the inhabitants are able to control it to some extent. So to the difficulty in predicting clothing and metabolic rate is added the problem of applying a steady-state model to an intrinsically variable situation.
3.4 Differences between the results from empirical and analytical investigations.

An additional problem has been found with the Fanger model. Some recent field surveys, in which clothing and activity descriptions were made for the subjects at the time of the survey, have shown the average values of PMV to be quite seriously different from the average comfort vote in such a way as to overestimate the discomfort of the environment. This means that buildings heated according to accepted standards will be overheated, and those cooled will be overcooled. The evidence for this effect is as yet based on fairly slender evidence, but it is sufficient to cast serious doubts on the reliability of this method, which is, after all, currently used by the heating and ventilation industry internationally to set indoor temperatures.

4 THE ADAPTIVE APPROACH

4.1 The adaptive mechanism

The adaptive approach to thermal comfort starts, not from a consideration of the heat exchange between man and the environment, but from the observation that there are a range of actions that man can and does take in order to achieve thermal comfort. The seat of temperature regulation in man is the temperature of the brain, from where he controls the equilibrium between himself and the environment by means of actions taken which tend to maintain this temperature within close limits. If a change occurs, in the environment or elsewhere, causing the brain temperature to deviate from these close limits, then an action is taken which will tend to restore it to these limits.

The types of action which can be taken are:

Sub-topic I. Modifying the internal heat generation: this can be achieved unconsciously with raised muscular tension or, in a more extreme situation, the shivering reflex, or consciously, for instance through jumping about in the cold to increase metabolic heat or having a siesta in the warm to reduce it.

Sub-topic II. Modifying the rate of body heat loss: achieved unconsciously through vasoregulation or sweating: consciously by such actions as changing ones clothing, cuddling up or by taking a cooling drink.

Sub-topic III. Modifying the thermal environment: through lighting a fire, opening a window, or in the longer term by insulating the loft or moving house.

Sub-topic IV. Selecting a different environment: within a room by moving closer to the fire or catching the breeze from a window, between rooms in the same house with different temperatures, or by moving house or visiting a friend.
All these are but examples of the actions which can be taken, and if we are always free to take all of the actions listed (and the hundreds of others which might be added), then thermal discomfort will not be a problem.

Figure 1 shows how workers in Pakistan used clothing and air movement (largely from fans) to keep comfortable at different indoor temperatures. Figure 2 shows how for different indoor temperatures the likelihood that given environmental controls are used will change. In this case the occupants are trying to change indoor conditions to suit their own requirements. Some of these are not direct, for instance blinds are often drawn to exclude solar radiation in hot conditions, this will result in greater use of lights an high temperatures. Windows may be used to increase air movement, but in very hot conditions may actually let in hot air from outside.

![Adaptive actions to change comfort temperature (Pakistan)](image)

Figure 1. Use of clothing and air movement by Pakistani workers to keep comfortable at different indoor temperatures (source: Roaf et al (2005) *Adapting Buildings and Cities for Climate Change*)
Figure 2. Use of controls. These are not all directly effecting the indoor temperature, but are generally a consequence of efforts to gain thermal or visual comfort. (source: Roaf et al (2005) *Adapting Buildings and Cities for Climate Change*)

There are also a number of constraints which limit our ability to take actions to avoid discomfort such as climate, cost and fashion. Having no direct control over the environment (as when in a big office the heating engineer sets the temperature for everyone) can increase the likelihood of discomfort. In addition many of the actions we could take to improve comfort have a distinct time constraint - building a new house, changing clothing, visiting a friend and so on all need time to complete. And most actions are limited in how far they can be successful, taking off a garment, for instance, can only compensate for a limited change in temperature.

The implication of the adaptive principal is that given sufficient time, people will find ways in which to adapt to any temperature so long as it does not pose a threat of heat stroke or hypothermia. Discomfort will arise where temperatures:

**Sub-topic I.** change too fast for adaptation to take place  
**Sub-topic II.** are outside normally accepted limits  
**Sub-topic III.** are unexpected  
**Sub-topic IV.** are outside individual control

### 4.2 Evidence of adaptation

Whilst the individual processes of adaptation are complex, the form of the process is that of a feed- back system. Because of this the end results can seem very simple.
Let us consider the effect of adaptation on the comfort temperature. Given time people will take adaptive measures to suit themselves to the average temperature they experience (note that some of the adaptation is expressed in the temperature itself, some in the person's adaption to it). So we would expect the comfort temperature to be close to the average temperature they experience. Using the results of field surveys, Humphreys (1981) has shown this to be very close to the real situation. The results of his survey are shown in Fig 1.

Figure 3 Relationship between comfort temperature (Tc) and mean temperature experienced (Tm)

The points in figure 1 each represent a field survey of thermal comfort. In each case Humphreys has calculated the comfort temperature predicted by the survey. He has plotted these against the average temperature experienced by the subjects in the survey. The slope of the regression lines in fig 4.1 are unity. There is a displacement of 2oK in the line for free running buildings. The reason for this is unexplained and could reflect a peculiarity of the data or a preference for being slightly warm in such buildings, possibly a mixture of the two. Humphreys discusses this in his paper. Nevertheless the relationship between average comfort temperature and average temperature experienced is clear to see.

There is much other evidence that a feedback or adaptive mechanism is at work, in such relationships as between clothing and temperature, indoor temperature and outdoor temperature and so on.

4.3 Setting Comfort standards using the adaptive model.
Comfort standards based on adaptive assumptions will be more than simply a temperature to aim at. The standard will need to reflect the interactions between comfort and environment in its formulation. Such concepts as predictability, constraint, variety, and control will need to be incorporated into the standard.

To start with the `comfort temperature' which we define as the temperature at which there is the least probability of discomfort, or at which satisfaction with the environment is most likely. The value of the comfort temperature will vary at the very least with climate and season. The value of the comfort temperature in free-running buildings can be deduced from a graph such as that shown as figure 2. Humphreys found that the best outdoor temperature predictor for the comfort temperature was the mean of the monthly mean minimum and the monthly mean maximum temperatures.

![Graph showing comfort temperature as a function of outdoor temperature](image)

**Figure 4** Comfort (or Neutral) temperature as a function of outdoor temperature (from Humphreys 1981)

In a building that is not free-running the comfort temperature is decided by social and economic factors and only slightly by climatic ones. The finding that people in America and Europe have a different comfort temperatures for broadly comparable populations illustrates the point. So the comfort temperature in such circumstances will require research among the local population. These variations occur not just between different populations, but within the same population between economic or social groups. These variations in comfort temperature are more difficult to formalise, and probably can be expressed as the need to provide variety and controllability so that people can choose for themselves.

The comfort temperature is not the only temperature which people can find
comfortable. Clearly there are allowable variations around it which will not cause discomfort. The amount of variation allowable will be time-dependent. This is because the longer people have to adapt the further they can change without significantly increased discomfort. Thus we might find that ±2K was the maximum allowable within-day variation with a maximum within-week variation of, say, ±5K. The implications of such dynamic temperature standards would be to change the way in which the designer investigates a building. The dynamic thermal characteristics of free-running buildings as well as the steady-state characteristics would be incorporated in design.

Another factor which needs clarification is the variability of temperature (and other factors) within a room. A model which seeks to explain thermal comfort needs to take into account the variations in conditions within a space, and the constraints on the ability of the occupants to make use of this variability. In conditions where people are able to move around, such variability may be a key factor in user satisfaction.

**Comfort temperatures for Islamabad, Pakistan**

![Temperature Chart](image)

*Figure 5 Outdoor mean temperatures in Peshawar, Pakistan, with indoor comfort temperature (Tc)*

Using the results of field studies of thermal comfort can allow the designer to predict the appropriate method of passive cooling in a building. Nicol (1994) has suggested that by superimposing the comfort temperature (derived from the outdoor temperature) on a graph of outdoor temperature (fig 3) suggests the relationship between indoor comfort and outdoor temperature. The role of the building in providing thermal comfort can then be deduced.

**4.4 Research needed**
There is a need for research on several fronts before such temperature standards can be formulated:

The adaptive ‘model’ is largely empirical and much of the explanation is speculative and based on supposition. In order for the ideas behind it to be confirmed and the insights it gives to be generalised scientifically much research needs to be conducted.

Present physical models are related to a heat steady-state exchange model. Recent advances in the development of dynamic thermal modelling of both the human body (physiological models) and the thermal environment (dynamic building simulation) open the way for a more rational approach which can provide an analytical model which can predict real situations in the field.

The calibration of such a model requires wide ranging work in the field, and in particular with the psychological aspects of the model, there may be no substitute for the empirical approach. Field studies and the insights they give us are the key to this understanding.

5 Indoor air quality

Exposure to pollutants in indoor air may cause a variety of effects. The severity of the effects covers a wide spectrum from perception of unwanted odours to cancer. The effects may be acute or develop over longer time. Some examples of health effects related with indoor air are:

- Dispersal of airborne infectious diseases
- Some micro-organisms can grow in air humidifiers and may result in pneumonia (Legionella) and "humidifier fever".
- High humidity indoors increases the risk for allergy. It is also associated with an increased growth of micro-organisms such as mould and bacteria. Some asthmatic children react on exposure to mould.
- An increased risk of developing lung cancer has been linked to exposure to environmental tobacco smoke (ETS) and to radon decay products.

For some effects, clear relationships with exposure to indoor air pollution have been reported. Among these are respiratory diseases (particularly amongst children), allergy (particularly to house dust mites) and mucous membrane irritation (particularly due to formaldehyde). Large numbers of people have been, and are still affected.

Many chemicals encountered in the indoor air are known or suspected to cause sensory irritation or stimulation at least at high concentrations. As pointed out by the WHO (1989), many different sensory systems that respond to irritants have receptors situated on or near the body surface. Some of these systems tend to facilitate the response rather than habituate and their reactions are delayed. On the other hand, in the case of odour perception, the reaction is immediate but also influenced by olfactory fatigue on prolonged exposures. In general, the sensory systems are tuned towards registering environmental
changes rather than the absolute levels. Sensory effects are important parameters in indoor air quality control for several reasons. They may appear as:

- adverse health effects on sensory systems (e.g., environmentally-induced sensory dysfunctions)
- adverse environmental perceptions which may be adverse per se or constitute precursors of disease to come on a long term basis (e.g., annoyance reactions, triggering of hypersensitivity reactions)
- sensory warnings of exposure to harmful environmental factors (e.g., odour of toxic sulphides, mucosal irritation due to formaldehyde)
- important tools in sensory bioassays for environmental characterisation (e.g., using the odour criterion for general ventilation requirements or for screening building materials to find those with low emissions of volatile organic compounds).

It is important to realise that the sensory effects of pollutants are not necessarily linked to their toxicity. Indeed some harmful air pollutants are not sensed at all. Therefore perceived air quality is not a universal measure of adverse effects.

Sensory effects reported to be associated with indoor air pollution are in most cases multisensory and the same perceptions or sensations may originate from different sources. Humans integrate different environmental signals to evaluate the total perceived air quality and to assess comfort or discomfort. However, it is not known how this integration occurs. Perceived air quality is for example mainly related to stimulation of both the nerves, trigeminal and olfactorius. Comfort and discomfort by definition are influenced by more complex psychological factors and for this reason the related symptoms, even when severe, cannot be documented without perceptual assessments. The same is of course true for perceptions.

(a) Ventilation and health

A recent meta-analysis of 20 field studies in office buildings involving more than 30000 subjects analysed the association of ventilation rates with human responses of perceptions and symptoms. Almost all studies found that ventilation rates below 10 l/s person in all building types were associated with statistically significant worsening in one or more health or perceived air quality outcomes. Some studies determine that increases in ventilation rates above 10 l/s person, up to approximately 20 l/s person, were associated with further significant decreases in symptoms or with further significant improvements in perceived air quality.

(b) Air quality and the urban context

Increased industrialisation and urbanisation have created important pollution problems in urban areas. Sulphur dioxide, particulate matter, nitrogen oxides,
carbon monoxide, etc., affect in a direct way the human health while affect historic monuments and buildings. It is calculated that the cost for damage only by sulphur dioxide to buildings and construction materials might be in the order of 10 billion ECU per year for the whole Europe.

Damage from increased pollutant is evident. Analysis of the relationship between hospital admissions and sulphur oxide levels in Athens, found that a "three fold increase in air pollutants doubles hospital admissions for the respiratory and cardiovascular disorders" and that "acute respiratory illness shows the highest correlation for the SO\(_2\) variable". Levels of nitrogen oxide are particularly high in urban environments. NO\(_2\) levels in San Francisco and New York exceeds 200 1g per cubic meter while in Athens the corresponding concentration is close to 160 1g per cubic meter, (OECD, 1983).

Health problems associated with the urban environment are mainly associated to the increased use of cars. This has been acknowledged by the British Medical Association, (1997). Pollution from gasoline and petrol has been proved to be partly responsible for heart diseases. In London, 1 in 50 heart attacks treated in hospitals were strongly linked with carbon monoxide which is mainly derived from motor vehicle exhausts.

Given the increased outdoor pollution levels in many urban regions, the assumption that ‘outdoor air’ is equivalent to ‘fresh air’ or ‘clean air’ is far from evident. With respect to ventilation, it means that the following elements become of increased importance:

**The location of air intake openings**
The increased average pollution levels in urban areas are due to increased emissions from transport, industry and building related emissions. One can find around buildings big variations in the pollution levels (e.g. between front and rear side of a building). Therefore, an appropriate location of the air intake openings is becoming an important parameter. For mechanical ventilation systems, this is mainly an organisational and technical problem, whereas the situation is less evident for natural ventilation systems. As a matter of fact, the use of ductwork for air supply is less evident for natural ventilation systems.

**Air cleaning**
- Air cleaning may be required for reducing the pollution levels in the supply air to acceptable levels. The technology exist for reducing particle and gas concentrations to acceptable levels, but the cost may be substantial and it will in most cases result in increased energy use due to higher pressure losses and the need of more fan power. In case of natural ventilation, air cleaning may be less evident, since the additional pressure losses may substantially reduce the air flow rates.

**Optimisation of air flow rates**
- The assumption that more ventilation will result in a better indoor air quality is clearly not valid in urban areas if the outdoor pollution levels are high.

**Indoor air quality and air flow rate requirements**
Whereas for thermal comfort, an optimum range can be defined, such situation does not exist for indoor air quality. As shown in , the number of dissatisfied people reduces with increased air flow rates. The 3 classes A, B and C as given in CEN CR 1752 (CEN, 1998) are indicated. For class A, the air flow rate (10 l/s.person) is 2.5 times higher than the required air flow rate for class C (4 l/s.person).

Whether or not other sources of pollution are taken into account will further widen the range in air flow specifications.

Hygro-thermal considerations for health

Indoor temperature and humidity can have an important bearing on the health of building occupants.

Temperature

Low indoor (and outdoor) temperatures during winter have long been associated with increased death rates – particularly among the elderly – from respiratory and cardiovascular disease. This has been found particularly among the populations of western and southern Europe where standards of insulation and indoor air quality in buildings tend to be lower (perhaps from a perception that these areas have less severe winters) (Eurowinter group, 1997). There is a positive trend in these figures associated with the introduction of comprehensive winter heating systems (central heating). Unfortunately the underlying poor quality of the buildings can mean that the costs of heating become prohibitive and fuel poverty (the inability to heat adequately due to high fuel costs and low income) becomes a problem.

Humidity

The occurrence of high humidity in buildings – particularly when accompanied by warm temperatures can encourage the presence dust mites particularly in buildings with carpets and other soft furnishings. The faeces of the dust mites are a strong allergen and the cause of asthma and other allergic diseases. High humidity can also be a strong factor in the growth of moulds. Moulds are not only unsightly but can also be associated with increased levels of allergic disease, probably caused by the spores which that generate.

Effect of temperature on Indoor Air Quality

The effect of air temperature on thermal comfort is well known, but its effect on air quality is not so widely recognised. Studies have shown that warm and humid air is stuffy, and warm room air temperature in the winter causes a higher number of typical sick building symptoms than cooler air (fig 4). The relationship between the number of symptoms and temperature is close to linear in the temperature range from 20 to 26 °C. Laboratory experiments have shown that perceived quality of polluted air depends on the enthalpy of the air. In laboratory tests, air was polluted with
emissions from typical building materials. The summary of the results are shown in Figure 5. Studies with a whole body exposure did not show as strong effect of the enthalpy of the air on perceived air quality. However, the influence was still very significant. These findings suggest the use of low room air temperature and low humidity in the winter from a standpoint of good IAQ and energy economy.

![Figure 5](image)

Figure 5: Emissions from typical building materials. The summary of the results are shown in Figure 5. Studies with a whole body exposure did not show as strong effect of the enthalpy of the air on perceived air quality. However, the influence was still very significant. These findings suggest the use of low room air temperature and low humidity in the winter from a standpoint of good IAQ and energy economy.

![Figure 6](image)

Figure 6: Number of sick building symptoms depending on the room air temperature in the winter time in an office building with approx. 1000 employees. Source: Seppänen and Jaakkola (1989).

![Figure 7](image)

Figure 7: Acceptability of air related to enthalpy at selected pollution levels of different materials. Source: Fang et al. (1998).

The target values of the air velocity in a room are also related to ventilation and energy efficiency. High velocities increase the convective heat transfer, thus the upper end of the comfort range of temperature should be used in a cooling situation, and lower end of the comfort range in a heating situation.

Typically, the average room air velocity increases with the cooling load and supply air flow rate. High supply air rates are thus desirable in a cooling situation, and low supply air rates in a heating situation. The air velocities can
also be affected by the air distribution system, or with a local fan such as a tropical ceiling fan. Displacement air distribution systems typically result in lower average air velocities in a room than a mixing air distribution system. The target value for the humidity of indoor air is of great significance in warm and humid climates in respect to energy consumption. An increase, for example, in the set point of the relative humidity from 40 % to 60 % has a significant impact on the energy requirements for those locations with significant cooling requirements. For example, the energy requirements of ventilation at a set point of 60 % relative humidity are only 56 % of the those at a set point of 40 % RH in Miami. (IEA/AIVC 47 1995).

6 Acoustic Comfort

6.1 Acoustic criteria

The specification of permitted background noise levels may be determined by acoustic performance, for instance being able to conduct a conversation, or by acoustic comfort where the noise is simply annoying or causing sleep disturbance.

1 The noise level or more specifically the sound pressure level within a space is determined by the sound power entering that space, be it from the outside or from within the space (e.g. a/c system, telephones, voices), and amount of sound absorbing material in the space (which with the size of the space determines its reverberation).

2 Within a space we consider two sound fields: the direct field and the reverberant or diffuse field. The former is the sound that comes direct from the source and is directional. The latter is the sound that is reflected off all the surfaces and is therefore 'diffuse'. If there are no reflective surfaces we talk of a free field situation.

6.2 Background noise

These may be specified in terms of an L_{Aeq} (the equivalent continuous "A" weighted sound pressure level) or in terms of the NR (noise rating) or NC (noise criteria). The former is more appropriate for varying noises such as traffic noise while the latter is more appropriate for steady noises such as air-conditioning noise.

<table>
<thead>
<tr>
<th>Perception</th>
<th>L_{Aeq}</th>
<th>NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Quiet</td>
<td>25-35</td>
<td>20-25</td>
</tr>
<tr>
<td>Quiet</td>
<td>35-45</td>
<td>30-35</td>
</tr>
<tr>
<td>Moderately</td>
<td>45-</td>
<td>40-</td>
</tr>
</tbody>
</table>
Typical background values

6.3 Urban noise sources

These may be specified in terms of an $L_{Aeq}$ (the equivalent continuous "A" weighted sound pressure level) or in terms of the NR (noise rating) or NC (noise criteria). The former is more appropriate for varying noises such as traffic noise while the latter is more appropriate for steady noises such as air-conditioning noise.

- Road Traffic Noise
- Aircraft Noise
- Train Noise
- Construction Site Noise
- Industrial and Commercial Noise
- Noise from Neighbours

6.3.1 Road traffic

6.4 Reverberation

The sound absorbing property of a material is defined in terms of the sound absorption coefficient ($\alpha$): The fraction of incident sound energy not reflected from a surface.

The absorption area of a space is calculated by adding together the absorption area of all the materials:

$$A = \alpha_1 S_1 + \alpha_2 S_2 + \ldots + \alpha_n S_n$$

where

$A$

Absorption area

$\alpha_1, \alpha_2 \ldots \alpha_n$

Sound absorption coefficients of the different surfaces in the space

$S_1, S_2 \ldots S_n$

is the surface area of the different material

This can also be expressed as
\[ A = \sum_{n=1}^{m} S_n \alpha_n \]

The reverberation time of the space is given by Sabine’s formula:

\[ T = 0.16 \frac{V}{A} \]

where

\( T \)
Reverberation time

\( A \)
Absorption area (defined above)

0.16
Empirical constant

\( V \)
is the volume of the space

<table>
<thead>
<tr>
<th>Space</th>
<th>Times</th>
</tr>
</thead>
<tbody>
<tr>
<td>Living room</td>
<td>0.5s</td>
</tr>
<tr>
<td>Office</td>
<td>0.3-0.5s</td>
</tr>
<tr>
<td>Theatre</td>
<td>1s</td>
</tr>
<tr>
<td>Concert Hall</td>
<td>2s</td>
</tr>
</tbody>
</table>

Typical reverberation times

### 6.5 Using absorption to reduce room noise

The reverberant noise level can be reduced in a space by the introduction of sound absorber.

1. The reduction in reverberant noise level is dependent on the ratio of the new absorption area (after addition of the new absorbing material) to the original absorption area

2. The reduction in sound pressure level

\[ L_p = 10 \log \frac{A_{new}}{A_{old}} \]

### 6.6 Levels

### 6.7 Room sound levels
The actual sound pressure level is a sum of the direct field and the reverberant field
\[
L_p = L_w + 10 \log \frac{Q}{4\pi r^2} + \frac{4}{R}
\]
where
\(L_p\)
  is the sound pressure level
\(L_w\)
  is the sound power level
\(r\)
  is the distance from the sound source
\(Q\)
  is the directivity of the source (\(Q=1\) in a free space and 2 if the source is on a hard reflecting surface)
\(R\)
  is the room constant \(\frac{S\alpha}{1-\alpha}\)

6.8 Attenuation of building facades

The attenuation or sound insulation of a building facade is nearly always determined by the glazing.

An open window in a building facade gives an attenuation of about 6dB whatever the glazing material.

The sound insulation of any material is principally a function of its mass although also affected at certain frequencies by resonances and bending waves. The insulation increases by 4-5 dB per doubling of mass and doubling of frequency. Hence all materials give better insulation at high frequencies.

Instead of doubling the mass better insulation is often obtained by using two separate sheets of the material such as in double glazing. In principle the insulation of the sheets can then be added. ie. two single sheets of glazing of insulation giving 20dB each would give 25dB when stuck together but 40dB when kept separate. The behaviour is not quite as simple as this and the insulation is less. Complex resonances occur and the best type of double window to choose is also determined by the incident sound spectrum (traffic, aircraft or train)
6.9 Noise and Natural ventilation

Domestic natural ventilation systems such as trickle ventilators as well as the larger openings associated with natural ventilation systems in commercial buildings (such as inlets for chimney exhaust systems) all admit noise.

1. The small holes associated with trickle ventilators are reasonable insulators against low frequency sound but the high frequencies squirt through. Essentially the insulation of a double glazed window will be reduced to that of a single glazed window (28 dBA) but with some detriment in performance at high frequencies.

2. Attenuators can be designed to produce an insulation equivalent to single glazing for the larger inlet systems. Careful design is necessary to limit the reduction in free area of the duct otherwise increased pressure losses will occur with reduction in natural ventilation.

6.10 Acoustic privacy

1. In open plan offices acoustic privacy requires a background noise level of NR=40 or $L_{Aeq}=45$ dB.

2. For cellular offices the situation is more complex. The minimum level of background noise is determined by the insulation of the partition. This is often quite low in a flexible office space due to sound transmission in the false ceiling. The privacy is best indicated in terms of background level + insulation.

<table>
<thead>
<tr>
<th>Audibility</th>
<th>dBA</th>
<th>NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intelligible</td>
<td>70</td>
<td>65</td>
</tr>
<tr>
<td>Unintelligible</td>
<td>80-90</td>
<td>75-85</td>
</tr>
<tr>
<td>Inaudible</td>
<td>&gt;90</td>
<td>&gt;85</td>
</tr>
</tbody>
</table>

*Sound perceived by occupant background noise plus insulation.*

REFERENCES


Nicol, Jamy, Sykes, Humphreys, Roaf and Hancock, 1993 A survey of thermal comfort in Pakistan toward new indoor temperature standards , School of Architecture, Oxford Brookes University.


