

## Chapter 2

# Thermal Indoor Environment

**Abstract** Room temperature and indoor air quality have a strong impact on the overall satisfaction with the thermal environment. Responses to our thermal indoor environment have a considerable effect on health, comfort, and performance. Formal methods have been developed to design the interior environment. Thermal comfort takes both global and local parameters as well as static and dynamic aspects into consideration.

The thermal indoor environment is a composition of many and diverse aspects. Hence, the perspective on thermal comfort may change its evaluation by occupants (Corgnati et al. 2011).

### 2.1 Human Responses to the Thermal Environment

Responses to our thermal indoor environment have a considerable effect on health, comfort, and performance. There has been considerable scientific investigation into these responses and formal methods have been developed to design and to develop the interior environment. Existing methods for the evaluation of the general thermal state of the body, both in comfort and under heat- or cold-stress considerations, are based on an analysis of the heat balance for the human body. Under cool to thermo-neutral conditions, heat gain is balanced by heat loss, no heat is stored, and body temperature equilibrates, that is:

$$S = M - W - C - R - E_{sk} - C_{res} - E_{res} - K \text{ in W/m}^2 \quad (2.1)$$

where:

- S Heat storage in the human body;
- M Metabolic heat production;
- W External work;
- C Heat loss by convection;
- R Heat loss by radiation;

|           |                                         |
|-----------|-----------------------------------------|
| $E_{sk}$  | Evaporative heat loss from skin;        |
| $C_{res}$ | Convective heat loss from respiration;  |
| $E_{res}$ | Evaporative heat loss from respiration; |
| $K$       | Heat loss by conduction.                |

The four environmental factors influencing this heat balance are: air and mean radiant temperature ( $^{\circ}\text{C}$ ), air speed (m/s), and partial water vapor pressure (Pa). The three personal variables are: metabolic heat production due to the activity level ( $\text{W}/\text{m}^2$  or met), the thermal resistance of clothing (clo or  $\text{m}^2\text{K}/\text{W}$ ), and the evaporative resistance of clothing ( $\text{m}^2\text{Pa}/\text{W}$ ). These parameters must be in balance so that the combined influence will result in a thermal storage equal to zero. A negative thermal storage indicates that the environment is too cool, and vice versa. In order to provide thermal comfort, the mean skin temperature also has to be within certain limits and the evaporative heat loss must be low.

Human responses to the thermal environment and to internal heat production serve to maintain a narrow range of internal body temperatures of  $36\text{--}38^{\circ}\text{C}$ . The human body has a very effective thermoregulation system, which uses blood flow for heat transport (high blood flow: enhanced heat dissipation—low blood flow: reduction of heat losses) with the hypothalamus acting as its main “thermostat.”

There are two categories of human responses to the thermal environment: voluntary or behavioral responses, and involuntary or physiological autonomic responses. Voluntary or behavioral responses generally consist of avoidance or reduction of thermal stress through modification of the body’s immediate environment or of clothing insulation. Physiological responses consist of peripheral vasoconstriction to reduce the body’s thermal conductance and increased heat production by involuntarily shivering in the cold, and of peripheral vasodilation to increase thermal conductance and secretion of sweat for evaporative cooling in hot environments. Autonomic responses are proportional to changes in internal and mean skin temperatures. Physiological responses also depend on the point in a diurnal cycle, on physical fitness, and on the sex of the individual. Behavioral responses rely on thermal sensations and discomfort. The latter appears to be closely related to the level of autonomic responses so that warm discomfort is closely related to skin wetness and cold discomfort similarly relates to cold extremities and shivering activity.

However, there is no physiological acclimatization to cold environments; the most common way to compensate for cold environments is behavioral adaptation by clothing adjustment. In warm environments, sweating is a very efficient way of losing heat. However, the sweat rate is limited, as well as how much a person can sweat during a day. Clothing, posture, and reduced activity are all behavioral ways of adapting to hot environments. Studies have also shown that people’s expectations may change and influence their acceptability of the thermal environment. Besides the general thermal state of the body, a person may find the thermal environment unacceptable or intolerable if the body experiences local influences from asymmetric radiation (opposite surfaces with high temperature differences,

solar radiation on single parts of the body, air velocities, vertical air-temperature differences or contact with hot or cold surfaces (floors, machinery, tools, etc.).

In existing standards, guidelines or handbooks, different methods are used to evaluate the general thermal state of the body in moderate, cold, and hot environments; but all are based on the heat balance and listed factors (EN ISO 7730:2005 2005; DIN EN ISO 11079:2007 2007).

Due to individual differences, it is impossible to specify a thermal environment that could satisfy everybody. There will always be a share of dissatisfied occupants. However, it is possible to specify environments that are likely to be acceptable for a certain percentage of the occupants. If they have some kind of personal control (change of clothing, setting of room temperature in a single office, increase of air velocity, change of activity level and posture), the overall satisfaction with the environment will increase significantly and every occupant may be satisfied. Due to local or national priorities, technical developments and climatic regions, a higher thermal quality (less dissatisfied occupants) or a lower one (more dissatisfied occupants) may be sufficient in some cases.

## 2.2 Health and Individual Performance

Besides influencing people's comfort, the thermal environment may also affect their health and performance:

- Extreme cold or hot environments are of high risk to the human body (heat stroke, frostbites, etc.). However, if thermal indoor conditions are less extreme, raised room temperatures have been associated with an increased prevalence of symptoms typical for the Sick Building Syndrome (SBS) or nonspecific, yet building-related symptoms such as headache, chest tightness, difficulty in breathing, fatigue, irritation of eyes and mucous membranes—all of which may be alleviated after the individual leaves the building (WHO 1983).
- Thermal conditions can affect productivity and work performance through several mechanisms, such as the following: thermal discomfort distracts attention and generates disorders that increase maintenance costs. SBS symptoms have a negative effect on mental work. Cold conditions lower finger temperatures and thus have a negative effect on manual dexterity. Rapid temperature swings have the same effects on office work as slightly raised room temperatures, while slow temperature swings cause discomfort that can lower concentration and increase disorders. Vertical thermal gradients reduce the perceived air quality or lead to a reduction in room temperature which then causes troubles of cold at floor level.
- The hypothesis that thermal conditions within the thermal comfort zone do not necessarily lead to optimum work performance is supported by the results of several studies. They showed that subjects performed best at a temperature

lower than thermal neutrality. However, a strong relationship between thermal sensation and relative office-work performance, based on a statistical analysis of data from laboratory and field measurements, is discussed with controversy. Some authors establish quantitative relations between indoor environmental quality and work performance and even derive a model that integrates the economic outcome of improved health and performance into building cost-benefit calculations, in conjunction with initial, energy and maintenance costs. Other authors interpret the results from these field studies from the users' perspective and conclude that their performance is strongly related to their satisfaction with the thermal environment. And user satisfaction is related to both their expectation and sensation of the thermal environment.

In the context of this guidebook, we assume that low-energy cooling improves the indoor environment, hence reduces negative health effects and improves the work performance. However, these effects have not been quantified or even economically evaluated.

## 2.3 Criteria for Thermal Comfort

Different physical parameters affect physiological reactions to the environment. Thus, these parameters (air, radiant and surface temperature, air velocity and humidity) are also the basis for defining criteria for an acceptable thermal environment. The criteria result in requirements for general thermal comfort (PMV/PPD index or operative temperature) and for local comfort disturbance (i.e., draft, radiant asymmetry, vertical air temperature differences and requirements on surface-temperature differences). They can be found in international standards and guidelines such as EN ISO 7730:2005 (2005), CEN/CR 1752 (2001), EN 15251:2007-08 (2007), and ASHRAE 55:2004-04 (2004), or in their national derivate respectively.

*Operative Room Temperature.* The most important criterion for the thermal environment is the operative temperature. As a sufficient approximation for most cases, it can be calculated as the arithmetic mean of the air temperature and the mean radiant temperature of surrounding surfaces in an occupied zone. Air temperature refers to the average value of the temperature in space and time in an occupied zone (ASHRAE 55:2004-04 2004). For a first general thermal comfort evaluation, a simplified calculation of the mean radiant temperature can be carried out, with surface temperatures weighted by the different surface areas.

*Parameters for Local Discomfort.* Besides the operative temperature, there are further temperature-related criteria to describe the thermal environment, particularly to assess local discomfort. The temperature asymmetry is also based on the radiant temperature of surfaces and is defined as the temperature difference between either two vertical (wall) or horizontal (ceiling and floor) surfaces. Another criterion is the absolute surface temperature, mainly important for the

floor to which the body has constant contact for long periods in many situations. Finally, the stratification of the air temperature has to be taken into account as a criterion for local comfort. Accepted temperature ranges for these three criteria can be found in EN ISO 7730:2005 (2005) and ASHRAE 55:2004-04 (2004).

*Humidity.* Humidity is addressed only as a boundary condition for general comfort [an upper limit is given in (ASHRAE 55)].

*Air Velocity.* Air velocity can be experienced either as draft sensation or may lead to improved thermal comfort under warm conditions. It may occur due to enforced air movement (open window/door, air outlet of ventilation system) or to buoyancy effects (air falling down along a cold window surface). Allowable air velocities and acceptable limits for draft rates—in terms of predicted percentage of people dissatisfied with draft—are summarized in (ISO 7730:2005 2005) and (ASHRAE 55:2004-04 2004). ISO 7730:2005 (2005) describes an allowance for higher air velocities in order to offset an increased operative room temperature, which was adopted by ASHRAE 55:2004-04 and in EN 15251:2005-07 standards.

## 2.4 Overall Satisfaction with the Thermal Environment

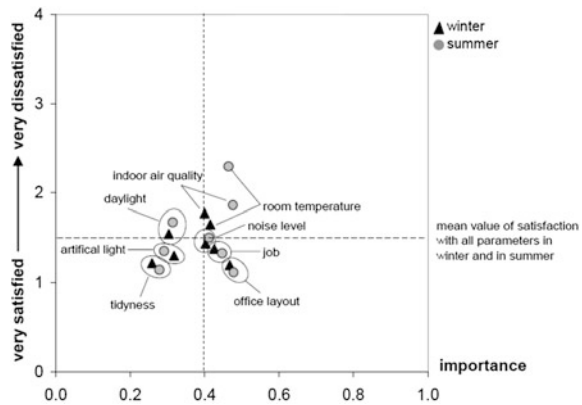
Further environmental parameters, e.g., air quality, visual or aural environment, can interact with the thermal environment and therefore influence thermal comfort or overall satisfaction in a space.

For most parameters describing the thermal environment, relationships between the parameter itself and a predicted percentage of people rating the indoor condition as (un)acceptable are established. People may be dissatisfied due to general thermal comfort and/or local thermal comfort parameters. However, there is no method for combining these percentages of dissatisfied persons to give a good prediction of the total number of occupants deeming the thermal environment unacceptable.

In comparison to the thermal environment, there is a large number of criteria and requirements for other indoor environment qualities such as air quality, visual and aural comfort. On the one hand, there is a possible physical interference of the different comfort requirements, e.g., for daylight and resulting solar heat gains through windows or recommended ventilation rates and noise from outside through open windows. On the other hand, the various comfort criteria have an impact on the (overall) occupants' satisfaction with the workplace and probably on thermal comfort. They also include social and architectural aspects related to a specific workspace. As there is not enough proof for quantitative correlations, their evaluation is only possible through a direct assessment after the building went under operation.

Figure 2.1 exemplarily shows a survey result for German office buildings. The subjective votes on satisfaction levels with different environmental parameters were given with respect to their relevance for the occupants' overall satisfaction with their workplaces (Gossauer and Wagner 2008).

**Fig. 2.1** Matrix with relevant satisfaction parameters from a field study in 17 German office buildings. The parameters are weighted by their correlation coefficients against the overall satisfaction with the workplace (importance of the parameter). For details of the survey, see (Gossauer and Wagner 2008)



The lower left field shows parameters with high satisfaction levels but the weighting calculation shows that they are less important for the general satisfaction with the workplace. In the lower right field, occupants are satisfied with the parameters that are more important for general satisfaction levels. The upper left square shows parameters with higher dissatisfaction but less importance for general satisfaction whereas parameters in the upper right combine higher dissatisfaction levels with higher importance for the general satisfaction with the workplace.

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