Chapter 2
Indoor Hygrothermal Conditions

Abstract The evaluation of indoor hygrothermal conditions is described, supported by a literature review. Involved parameters and standardized methodologies are summarized. The procedures for evaluation of human comfort are also briefly described.

2.1 Involved Parameters

The search for a safe and comfortable environment has always been a major concern for humanity. In recent decades the occupancy levels of the buildings, the construction practices (lower air permeability of the envelope and the generalized use of heating, ventilation and air conditioning (HVAC) systems) and the users' expectations have dramatically changed, leading to a growing interest in the theme of the indoor environmental quality. In fact, nowadays the indoor environmental quality is an important factor for the health, comfort and performance of populations, since in developed areas of the planet people spend most of their time inside buildings (Wargocki 2009). The concept of indoor environmental quality is very broad and depends on many variables such as temperature, relative humidity, air velocity, air flow, occupancy, concentration of pollutants, noise, lighting… Yet, thermal comfort is unanimously recognised as crucial for an adequate indoor environmental quality (Alfano et al. 2010).

The classic definition of thermal comfort is the one presented by Fanger (1970) describing it as "the state of mind in which a person expresses satisfaction with the thermal environment". Afterwards several authors defended that satisfaction with the thermal environment depends, in addition to the physical factors that determine the heat exchange between the human body and the environment in which he is located (thermal balance), of other factors such as social, cultural and

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psychological, which justify the different perceptions and responses for the same sensory stimuli. Therefore, users' past experiences and expectations may play a key role.

Several researchers had addressed their attention to the evaluation and quantification of thermal comfort in indoor environments. The main idea is to better understand which variables are involved, how it can be achieved, its impact in terms of occupants' health and productivity and how it can be quantified. Classical theories consider that thermal comfort depends on both individual and environmental factors as follows:

- Individual factors: metabolic rate, M [met]; and clothing insulation, I_{CL} [clo];
- Environmental factors: air temperature, T_a [°C]; mean radiant temperature, T_{mr} [°C], air velocity, v_{ar} [m/s]; and water vapor pressure, p_a [Pa].

For many years, the correct combination of these environmental factors which leads to comfort conditions has been pursued and several models to quantify an indoor environment on a single hygrothermal index have been proposed. Yet, in long term monitoring and in building simulation, comfort is commonly assessed just by the air temperature and relative humidity (Almeida and Freitas 2014; Olesen et al. 2011; Barbosa et al. 2015) and several simplified models, some included in national regulations and international standards, only use these two parameters, or simply the air temperature, to establish comfort conditions.

2.1.1 Air Temperature

Air temperature is the most important variable for thermal comfort quantification, since the sense of comfort in based on heat exchanges between body and environment and, therefore, enhanced by the temperature gradient between them (Lamberts 2005). Sometimes, only air temperature is used to establish comfort conditions. For instance, the Portuguese regulation defines thermal comfort based on air temperature: 20 °C in winter and 25 °C in summer.

2.1.2 Relative Humidity

Although often underestimated or even ignored compared to air temperature, relative humidity affects thermal comfort (ISO 2005; ASHRAE 2010), indoor air quality perception (Fang et al. 1998), occupants' health (Bornehag et al. 2001) and even building's energy consumption (Simonson 2000). Concerning thermal comfort, instead of global comfort, relative humidity is often linked to local comfort (Simonson et al. 2001).

2.2 Standardized Methodologies

In the 70s, based on Fanger's studies, ASHRAE presented a seven-level scale for thermal comfort assessment (Table 2.1). This scale became dominant in thermal comfort studies, being adopted in ISO 7730 (ISO 2005) and ASHRAE 55 (ASHRAE 2010) standards.

Fanger (1970) derived a general equation of comfort that attempts to include the effect of both individual and environmental factors. This index estimates the average vote for a group of persons of different nationalities, ages and sexes, according to the previous mentioned scale (Table 2.1) and was designated as *Predicted Mean Vote* (PMV). Fanger also suggested that the percentage of people who considered the environment as uncomfortable (feeling hot or cold) is related to their average vote, defining a second index called the *Predicted Percentage Dissatisfied* (PPD). PMV and PPD are commonly used as reference values in international standards to establish comfort conditions.

Yet, for long term monitoring of buildings' performance in service conditions, simpler methods based on air temperature and relative humidity are often used.

A simplified graphical method (Fig. 2.1) to evaluate thermal comfort is proposed in ASHRAE 55 (ASHRAE 2010). This method is applicable to environments with air velocity below 0.2 m/s, where the occupants' activities are sedentary (ranging between 1.0 met and 1.3 met) and clothing insulation varies from 0.5 to 1.0 clo. The comfort zone is for 80 % occupant acceptability, resulting from the combined effect of 10 % dissatisfied due to discomfort related to the whole body and 10 % that may occur from local thermal discomfort. The method establishes a comfort zone on a psychometric chart, requiring the operative temperature, which for moderate environments is often approximated by the air temperature, and the humidity ratio as inputs.

Adaptive models such as the ones suggested in ASHRAE 55 (2010) and EN 15271 (2007) only use air temperature as indicator of comfort.

ASHRAE 55 (2010) proposes a graphical method for indoor thermal comfort evaluation (Fig. 2.2), which can be applied to spaces where the occupants are engaged in near-sedentary physical activities, with metabolic rates ranging from 1.0 to 1.3 met. The base equation of the model was proposed by Brager et al. (2004), which establishes the indoor operative temperature, T_{oc}, as follows:

Table 2.1 Thermal comfort scale (adapted from ISO 2005 and ASHRAE 2010)

+3	Hot	Uncomfortable
+2	Warm	
+1	Slightly warm	Comfortable
0	Neutral	
–1	Slightly cool	
–2	Cool	Uncomfortable
–3	Cold	

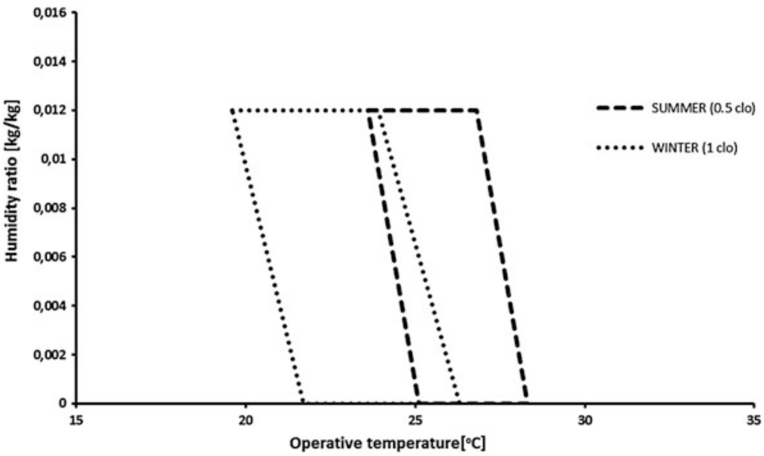

Fig. 2.1 Graphic comfort zone method (adapted from ASHRAE 2010)

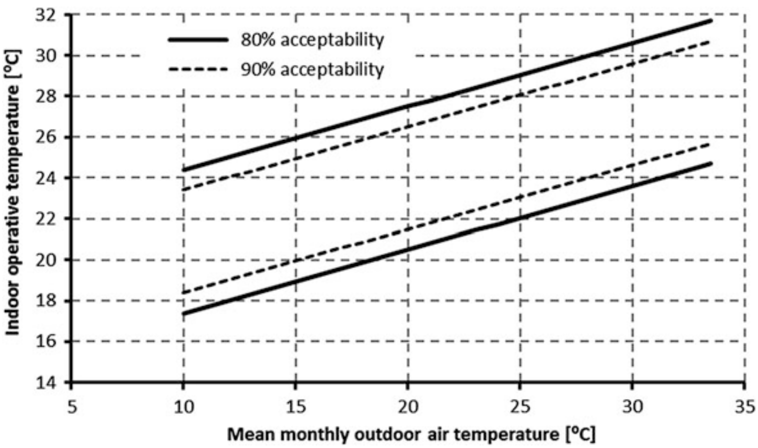

Fig. 2.2 ASHRAE adaptive model (adapted from ASHRAE 2010)

$$T_{oc} = 17.8 + 0.31 \cdot T_m \tag{2.1}$$

in which
T_{oc} [°C] Indoor operative temperature
T_m [°C] Mean monthly outdoor air temperature

EN 15251 (2007) proposes another graphical method for thermal comfort evaluation (Fig. 2.3). This model defines the operative temperature as function of the weekly running mean outdoor temperature as follows:

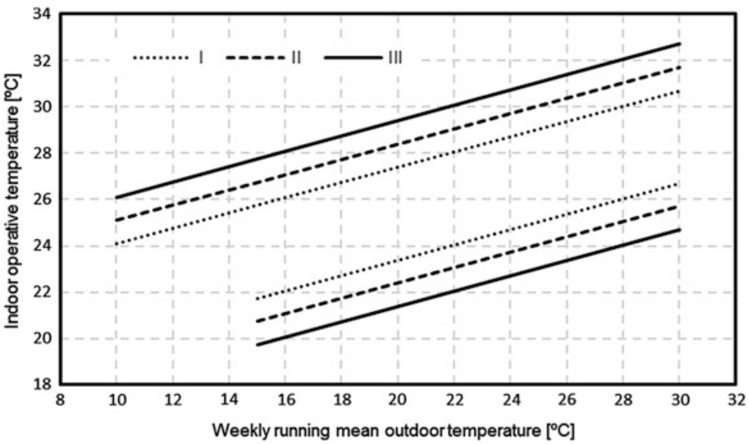

Fig. 2.3 EN 15251 adaptive model (EN 15251 2007)

$$T_{oc} = 0.33 \cdot T_{mp} + 18.8 \tag{2.2}$$

in which

T_{mp} [°C] Weekly running mean outdoor temperature

This model is applicable in buildings without cooling devices and considers three categories, which establish the users' comfort demand (dissatisfied percentage limit requirement). Each category assumes a comfort temperature interval that corresponds to the distance between lower and upper limits in Fig. 2.2. The model is mainly suitable for summer conditions but can also be used for winter season (weekly running mean outdoor temperature between 10 and 15 °C) assuming the same temperature limits as for mechanically ventilated buildings. This method is valid for office buildings and other buildings of similar type used mainly for human occupancy with mainly sedentary activities and dwellings, where there is easy access to operable windows and occupants may freely adapt their clothing to the indoor and/or outdoor thermal conditions.

Although applicable for long term evaluation of the indoor environment, there are no normalized procedures establishing the required sample size and how the results should be analysed when one uses these models. Commonly, the interpretation of the results is performed with simple indicators such as the "total hours of discomfort". If additional information as buildings' characteristics, occupancy, energy consumption or other is also available, a large number of data must therefore be combined and data-mining techniques arise as valuable tools for finding meaningful correlations among them.

2.3 Literature Review

The ease of access to portable sensors for measuring and recording both the users' behaviour and the indoor environmental conditions of buildings, generalized conducting long term monitoring campaigns whose result is commonly a very large number of data whose interpretation is not always easy. On the other hand, the use of modern data mining techniques has evolved considerably since the 90s, starting its widespread use in fields as diverse as economics, sociology or computer science. However, the use of these tools in the area of building science only began to emerge in significant number in recent years.

In this sense, in recent years, some research where data mining techniques are applied in the construction area has emerged. These include, for example, studies which seek to relate the performance of buildings with the users' behaviour or seeking to define the indicators that best represent the building's performance.

Data mining techniques, by enabling to extract new and relevant information from a large number of data, are especially suitable for works of this nature, where repeatedly arise phenomena whose quantification is difficult, as in the case of the users' behaviour, clearly affected by both physiological and psychological parameters.

2.3.1 Building Performance Versus User Behaviour

The recognition of behavioural patterns from a wide range of observations is accepted as a high potential alternative. These patterns tend to anticipate and replicate actions usually repeated by users. These patterns are crossed with performance measurements of buildings, seeking to correlations between them. This approach has been used to explain aspects related to the energy efficiency and the hygrothermal performance of buildings.

D'Oca and Hong (2014) used cluster analysis and association rules to identify valid window operational patterns in measured data. Yang et al. (2015) studied the role of households' attitudes in building's energy consumption by analysing the behavioural variability. Ren et al. (2015) applied data mining techniques to understand the operation and performance of space heating systems for improving the occupant comfort while reducing energy use. Brown et al. (2015) investigated the impact of physical, behavioural and demographic variables in the buildings' energy and water consumption.

2.3.2 Building Performance Indicators

Post-occupancy assessment is crucial in the evaluation of building performance as a well-known gap exists between the predicted and real performance of buildings

(Meneses et al. 2012). There is a growing interest in this issue and post-occupancy evaluation assumes as the key for a better understanding on how the design process can be improved. Most of the approaches try to establish key performance indicators which characterize the buildings' consumption and performance patterns.

Lourenço et al. (2014) selected schools energy key performance indicators from the results of a survey conducted in eight Portuguese secondary schools. Shahrokni et al. (2014) evaluated the energy efficiency potential of the city of Stockholm from the billing meter data of the housing stock. Tian et al. (2014) used an office building as case study for applying bootstrap techniques to improve the accuracy of the model selected for thermal performance analysis. Goçer et al. (2015) discussed the importance of post-occupancy evaluation for an effective building design process.

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Ramos, N.M.M.; Delgado, J.M.P.Q.; Almeida, R.; Simões,
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