Chapter 2
Indoor Environmental Quality

Abstract This chapter starts by explaining the notion of indoor environmental quality. Afterwards a complete description of thermal comfort and indoor air quality is provided. The thermal comfort concept, the factors that most influence it and the criteria for thermal comfort assessment, including the adaptive models, are described in detail. Regarding the indoor air quality, the most important pollutants are presented, including their concentration limits currently in force in Portugal.

Keywords Indoor environmental quality · Thermal comfort · Indoor air quality

2.1 Introduction

The search for a safe and comfortable environment has always been a major concern for humanity. In ancient times people used the experience acquired over the years to achieve adequate living conditions, making the best use of the available resources. The Greek writer Xenophon, in his memoirs, shares some of the teachings of the Greek philosopher Socrates (470–399 BC) about proper orientation of buildings, in order to have cool houses in summer and warm in winter. In the 1st century BC, Romans conceived a technique for central heating based on the use of double floors with a cavity where warm air from a fireplace flows (Florides et al. 2002). Also in the same period, Romans started using materials such as mica or glass for windows, both admitting the entry of light into the house and protecting it from the wind and rain. In Persia, on the other hand, a first effort for night ventilation was tested. Predominant wind was used as cool air during the night, providing a cooler environment during the day (Kreider and Rabl 1994).

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 environment quality. In fact, nowadays the indoor environment quality is an important factor for the health, comfort and performance of populations, since in developed areas of the

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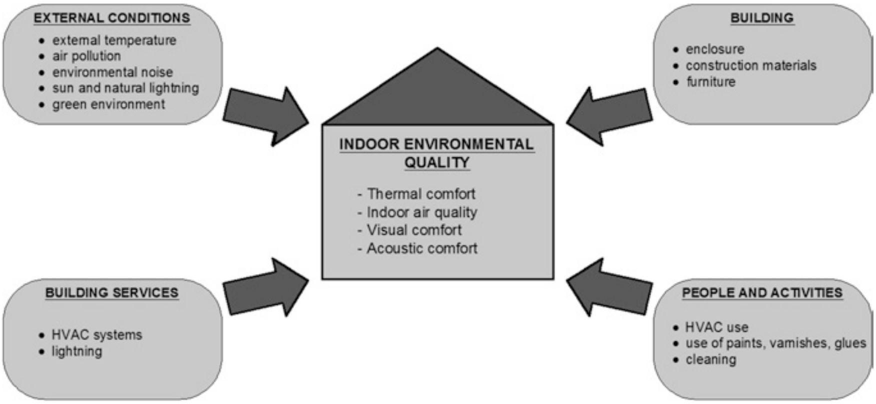

Fig. 2.1 Indoor environmental quality (adapted from REHVA 2010)

planet people spend most of their time inside buildings (Wargocki 2009). In addition, indoor environmental factors significantly affect the energy consumption of a building and, therefore, their evaluation and quantification during the design process has been widely debated (Santamouris et al. 2008; Alfano et al. 2010).

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… These can be grouped into four major areas that define the quality of the environment inside a space, namely (Franchimon et al. 2009; Alfano et al. 2010):

- Thermal comfort;
- Indoor air quality;
- Visual comfort;
- Acoustic comfort.

Indoor environmental quality evaluation depends on numerous factors that can be subdivided into four categories: external conditions, building, building services and human activities (REHVA 2010). Figure 2.1 schematically presents those variables and factors. Within this book objectives only thermal comfort and air quality are discussed and detailed in the following sections.

2.2 Thermal Comfort

2.2.1 Introduction

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

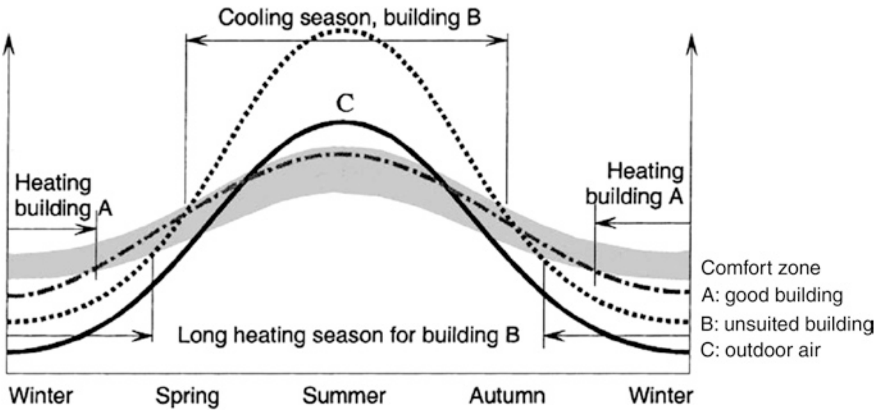

Fig. 2.2 Annual temperature fluctuation on a free floating building (adapted from Roulet 2001)

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

According to Chatelet et al. (1998) in a passive building without heating or cooling systems, the indoor environment should be at least as comfortable as the outside environment. This idea is reflected in Fig. 2.2, applicable to residential buildings. The comfort zone is wider in summer than in winter, since people' needs and requirements vary due to changes in their clothing.

An ill-conceived building design will only ensure comfort condition through high energy consumption since HVAC systems must be used for heating in winter and cooling in summer (De Dear and Bragger 1998).

2.2.2 Thermal Exchanges, Thermoregulation Mechanisms and Heat Balance

Man is a homoeothermic organism since maintains a relatively constant and warm body temperature independent of environmental temperature. To guarantee this condition body uses oxygen for the process of metabolism, producing internal heat. This energy must be dissipated to guarantee equilibrium. For a person to be comfortable it is necessary that at least his body is in thermal equilibrium, that is, the energy produced must be equal to the losses.

When no equilibrium is achieved, body temperature, which is around 36 ± 1 °C, tends to increase or decrease and might cause health problems and, in extreme cases, even death. For this reason human body has mechanisms to maintain internal temperature approximately constant, which are activated when the external environment conditions exceed certain limits.

The center control organ for human body temperature is the hypothalamus, located in the brain, which has a function similar to a thermostat. The internal temperature may vary slightly depending on the physiological conditions and on the signals that the hypothalamus receives from the nervous system. Thus, in cold environments internal temperature can drop and, consequently, heat losses diminish. Heat is conserved by vasoconstriction (skin blood flow is reduced). Moreover, in warm environments the internal temperature can rise, with increased heat losses. Internal heat is transferred for the skin through vasodilation (skin blood flow is increased) facilitating its transfer to the environment (Astrand and Rodahl 1986).

The thermal exchanges between the human body and the surrounding environment occur through heat transfer from the warmer to the colder element until equal temperatures are established. This corresponds to a heat transfer situation between two systems, enhanced by the temperature difference between them. It can occur in the following ways:

- Conduction: is the transfer of internal energy by direct contact between parts of the body and the surrounding environment due to a temperature gradient;
- Convection: is the transfer of energy between an object and its environment, due to fluid motion (air movement around the human body);
- Radiation: is the transfer of energy by electromagnetic waves between human skin and the surrounding environment due to a temperature gradient;
- Respiration: is the transfer of energy due to a temperature gradient between air breathe in and out;
- Evaporation: is the transfer of energy for the surrounding environment due moisture evaporation from the skin.

A resting adult produces approximately 100 W of heat. If the clothing and the environmental conditions are suitable, the heat losses are equivalent and, therefore, the heat balance is null and the person feels thermally neutral.

With increasing environmental temperature heat exchanges by conduction, convection and radiation decrease and evaporation should compensate to ensure thermal equilibrium. However, evaporation due to sweat is associated with an increase in temperature and might cause a discomfort feeling.

With decreasing environmental temperature heat exchanges by conduction, convection and radiation increase and the total energy losses are higher than the equilibrium value. The physiological response to this condition is to reduce the blood flow, decreasing the temperature gradient. In this situation a cold feeling appears and cloth changing can be the response.

Therefore, to ensure thermal comfort heat exchanges must remain within a relatively narrow range (Nilsson 2004).

As mentioned human thermoregulation mechanisms maintain body temperature approximately constant, forcing for an equilibrium between the internal generated heat and transfers for the surrounding environment (Fig. 2.3).

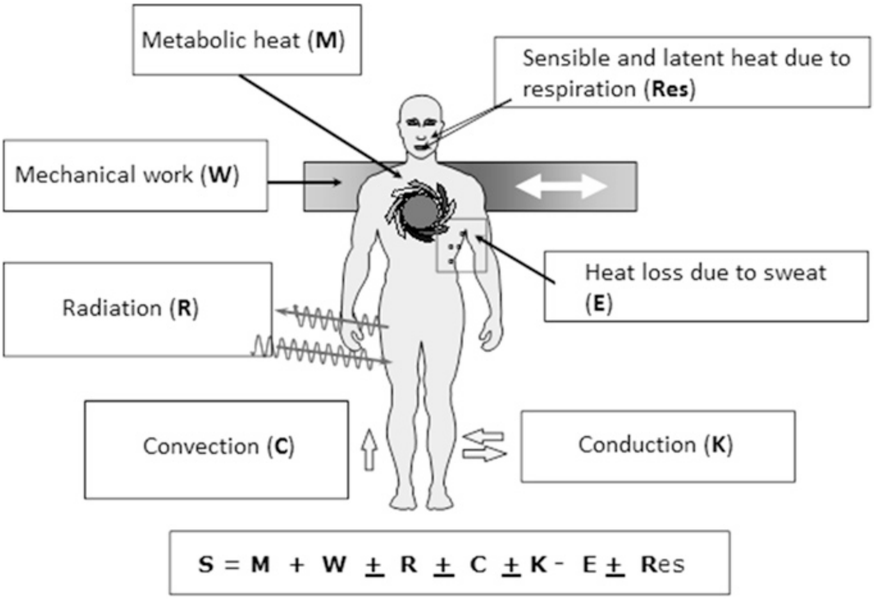

Fig. 2.3 Heat balance of the human body (adapted from Silva 2006)

This balance is described in the following equation where thermal equilibrium corresponds to a null S value:

$$S = M \pm W \pm R \pm C \pm K - E \pm Res \quad (2.1)$$

2.2.3 Factors Influencing Thermal Comfort

According to Fanger (1970) thermal comfort depends on six factors, two individual and four environmental:

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

These factors are decisive for equilibrium in steady state conditions. However, besides these, other more subjective (psychosocial parameters) are also important for thermal comfort perception in a given environment (Matias 2010).

Metabolic rate is related to the physiological process by which human beings produce energy from organic substances (metabolic process). The greater the physical activity, greater metabolic production and, consequently, internal heat generation. Metabolic rate is commonly express as generated energy per unit DuBois area. The unit is *met*, defined as the metabolic rate of a sedentary person (seated, quiet): 1 met = 58.2 W/m^2. This value is based on an average male adult (A_D = 1.8 m^2)

(ASHRAE 2009). Metabolic rate depends varies depending on the activity and typical values can be found in ISO 7730 (ISO 2005) and ASHRAE 55 (ASHRAE 2010).

Body exchanges heat with the clothing, which in turn exchanges it with the surrounding environment. These exchanges depend on clothing insulation. Additionally, garment also has the effect of reducing the body's sensitivity to air velocity and temperature variations. Clothing insulation depends on several factors such as type of fabric, fiber and body fit, and it can be expressed in *clo* units: 1 clo = 0.155 (m^2 K)/W. Typical values for clothing insulation can be found in ISO 7730 (ISO 2005) and ASHRAE 55 (ASHRAE 2010).

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. Portuguese regulation defines comfort based on air temperature: 20 ºC in winter and 25 ºC in summer.

Mean radiant temperature is defined as the uniform surface temperature of an imaginary enclosure in which an occupant transfers the same amount of radiant heat as in the actual non-uniform enclosure (ASHRAE 2010). It is the weighted average of the surrounding surfaces temperature of the enclosure, including the effect of solar radiation. Mathematically the exact calculation of this parameter is not simple since besides being required temperature, emissivity and area of all surfaces, it is also necessary to quantify angle factors between the person and each surface. Furthermore, when direct exposure to solar radiation is present, complexity significantly increases (Matias 2010). Thus, in practice an estimation of mean radiant temperature is used, based on measurements through a globe thermometer.

Air velocity is defines as the magnitude of the air flow velocity vector at the measuring point. It is important to include its effect in indoor environments due to its direct involvement in heat exchanges by convection and evaporation. In indoor environments air velocity is independent of wind and typically ranges below 1 m/s. Air movement occurs due to a temperature gradient, where hot air rises and cold air sinks (natural convection). When air movement is forced, by a fan for instance, convection coefficient rises, increasing heat losses (forced convection). Air velocity also has an effect on heat losses due to evaporation by removing moisture from the skin surface more efficiently, reducing the feeling of warm (Lamberts 2005).

Water vapor pressure is directly related to relative humidity. Corresponds to the pressure which water vapor would exert if it occupies the entire volume occupied by the moist air at the same temperature. It is formed by water evaporation. At a given temperature air can only contain a certain amount of water (saturated air), and above this value the condensation phenomenon occurs, increasing the surface temperature where it occurs. This process enhances the heat transfer between one body losing heat by evaporation, which is transferred to another where condensation occurs.

Water vapor pressure and air velocity are involved in heat exchanges by evaporation. Since approximately 25 % of generated body energy is eliminated as latent heat, it is important to guarantee environmental conditions which enhances these losses. As air temperature increases, convection and radiation losses decrease and body have to compensate by increasing evaporation. The higher the relative humidity, the lower the evaporation efficiency, and, therefore, suitable ventilation is required to control the amount of water vapor in the air.

2.2.4 Criteria for Thermal Comfort

For many years, the correct combination of environmental factors that leads to comfort conditions has been pursued by numerous researchers. Thus, several attempts have been proposed to quantify an indoor environment on a single hygrothermal index. The idea is to use it to establish admissible comfort limits for that environment. Typically, environmental parameters are combined for constant values of metabolic rate and clothing insulation—charts and nomographs.

In the 70's, 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 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). The PMV equation was derived from a statistical analysis of the results obtained in numerous experiments (more than 1300) carried out under controlled environmental conditions where people were asked to quantify the environment. PMV can be used both for thermal comfort verification and to establish minimum acceptable limits for a specific comfort level. Although it was derived for steady-state conditions, it can be used as a good approximation when one or two input parameters have small variations. 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). The relationship between the two indices is as follows:

$$PPD = 100 - 95 \times e^{\left(-0.03353 \times PMV^4 - 0.2179 \times PMV^2\right)} \tag{2.2}$$

According to this model it is impossible that all people feel comfortable in a given space for a given time. Even for a thermal comfort condition in which the average vote corresponds to a sense of neutral/comfortable, which corresponds to a PMV = 0, there are still 5 % of people uncomfortable.

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	

Table 2.2 Thermal environment categories (adapted from ISO 2005)

Category	Thermal state of the body as whole	
	PPD [%]	PMV
A	<6	$-0.2 < \text{PMV} < +0.2$
B	<10	$-0.5 < \text{PMV} < +0.5$
C	<15	$-0.7 < \text{PMV} < +0.7$

PMV and PPD are commonly used as reference values in international standards to establish comfort conditions. ASHRAE Standard 55 (ASHRAE 2010) states that the condition to be met is:

$$-0.5 < \text{PMV} < +0.5 \text{ or } PPD < 10\,\%$$

This condition also appears in standard ISO 7730 (ISO 2005), corresponding to category B. This standard proposes three categories (A, B and C) to classify buildings thermal environment. This approach considers that comfort limits do not have to be the same in all spaces, since local or technical conditions may suggest different targets. The limits proposed by the standard are presented in Table 2.2.

A simplified graphical method (Fig. 2.4) to evaluate thermal comfort is also proposed by ASHRAE Standard 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 and 1.3 met) and clothing insulation varies from 0.5 to 1.0 clo.

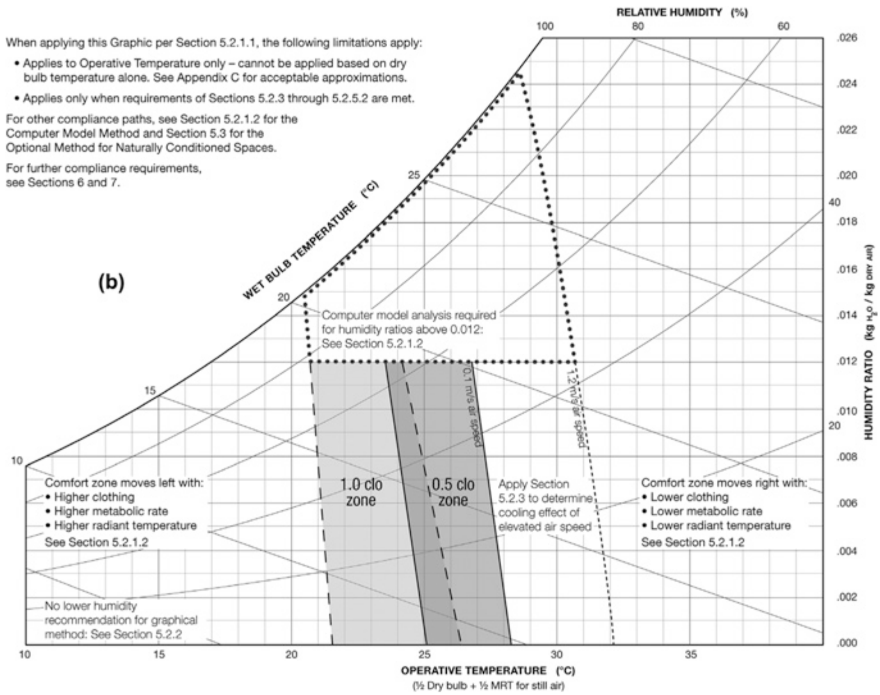

Fig. 2.4 Graphic comfort zone method (ASHRAE 2010)

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.

2.2.5 Adaptive Models

There are two ways of tackling thermal comfort issues. The first, previously described, corresponds to an analytical approach, based on experimental results in climatic chambers and using the heat balance equation considering a steady state regime. The second approach, called adaptive model, assumes a dynamic regime in which an individual can interact physically and psychologically with the environment that surrounds him. This alternative method to the conventional theory of thermal comfort believes that an individual has a fundamental role in the creation of his own thermal environment, through the way he interacts with the environment, modifying behaviors and habits or gradually adapting his expectations (Brager and de Dear 1998).

The interest in adaptive thermal comfort models began in the 70's in response to the energy crisis experienced at the time and, in recent years, regained interest from the scientific community due to climate changes. Allowing people to control the indoor environment, letting the interior air temperature to be closer to the exterior, may correspond to an important improvement in both comfort conditions and energy consumption (Milne 1995).

Adaptive models usually considered three forms of adaptation to the environment (De Dear et al. 1997):

- Behavioral: all actions consciously or unconsciously taken to ensure thermal equilibrium;
- Physiological: changes performed by the thermoregulation mechanisms, during a certain period of time, to adjust the body response to the environmental conditions;
- Psychological: effects of cognitive and cultural variables, and describes the extent to which habituation and expectation alter thermal perceptions.

Adaptive models are also present in international standards such as ASHRAE 55 (ASHRAE 2010), which includes a graphical method for indoor thermal comfort evaluation (Fig. 2.5).

This method 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}:

$$T_{oc} = 17.8 + 0.31 \cdot T_m \tag{2.3}$$

in which

T_{oc} [ºC] Indoor operative temperature
T_m [ºC] Mean monthly outdoor air temperature

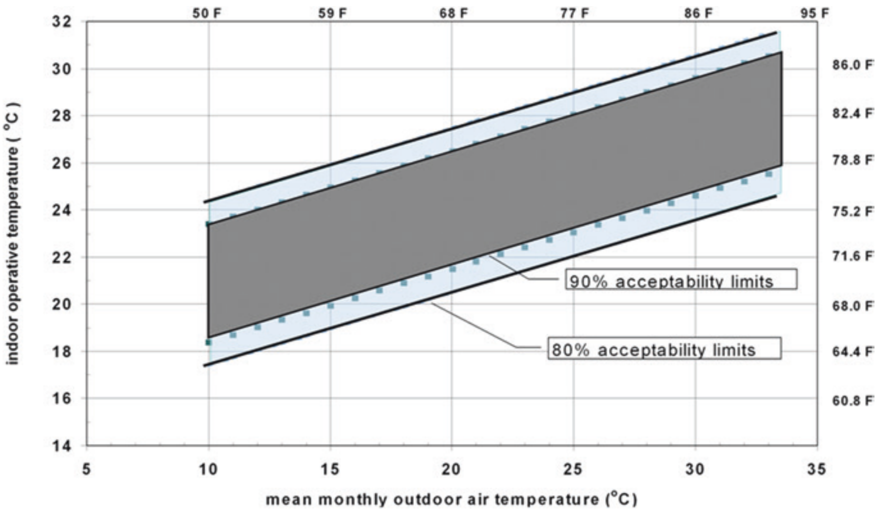

Fig. 2.5 ASHRAE adaptive model (ASHRAE 2010)

The 80 % acceptability limits are for typical applications and accepts ±3.5 ºC around the comfort temperature; the 90 % acceptability limits should be used when a higher standard of thermal comfort is desired and accepts ±2.5 ºC around the comfort temperature.

2.3 Indoor Air Quality

2.3.1 Introduction

Acceptable indoor air quality is defined in ASHRAE standard 62.1 (ASHRAE 2004) as air where there are no known contaminants in hazardous concentrations, determined according with the recognized authorities recommendations, and where a majority (at least 80 %) of the exposed occupants do not express dissatisfaction.

Over the past years, efforts were made in the building industry to increase indoor thermal comfort. In the 70's, the oil crises emphasized the need for energy conservation and building airtightness was improved, minimizing heat losses. However, inside buildings pollutants are also produced. In fact, indoor air quality can affected by various contaminants, not only from external sources but also internal ones. The outside air enters the building through ventilation and, additionally, furniture, construction materials, people and poor maintenance of HVAC systems can be a source of indoor pollution (REHVA 2010).

In 1984, a World Health Organization (WHO) report (1984) indicated that 30 % of buildings, new or rehabilitated, revealed excessive levels of air pollutants. This

Table 2.3 Pollutants concentration limits

Pollutants	Concentration limit
Particulate matter, PM_{10}	50 $\mu g/m^3$
Particulate matter, $PM_{2.5}$	25 $\mu g/m^3$
Volatile organic compounds, VOCs	600 $\mu g/m^3$
Carbon monoxide, CO	10 mg/m^3/9 ppm
Formaldehyde, CH_2O	100 $\mu g/m^3$/0.08 ppm
Carbon dioxide, CO_2	2250 mg/ m^3/1250 ppm
Radon, Rn	400 Bq/m^3

problem led to the "Sick Building Syndrome", used to describe situations in which building occupants suffer from health problems related to the time they spend inside the building and no specific cause can be detected.

2.3.2 Indoor Air Pollutants

Indoor air quality must on the one hand prevent pollutants from reaching concentrations that may endanger occupants' health and on the other maintain a pleasant environment (Viegas 2000).

In Portugal, indoor air quality is regulated in a national standard, which defines concentration limits for the most common indoor pollutants (see Table 2.3).

When one analyses indoor air quality in educational buildings, carbon dioxide arises as the most important indicator since it is a product of human respiration and typically these buildings present high occupancy levels. Therefore, in several international standards, is common to find carbon dioxide maximum concentration as the air quality criterion for classrooms.

Carbon dioxide is an odorless, tasteless and colorless non-flammable gas, which is present in exterior air with concentrations around 380 ppm (680 mg/m^3) (in unpolluted regions).

Usually, CO_2 concentration in buildings is very low and, therefore, harmless. However, in very high concentrations, which can occur in classrooms due to their high occupancy and low levels of ventilation, CO_2 can cause breathing problems, difficulty in concentration and headaches.

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