Indoor climate

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Abstract. In industrialized countries most of the time is spent indoors. The basic ambient parameters for a thermally comfortable indoor climate are air temperature, air velocity, humidity and radiation pattern. Besides the thermal component, the concentrations of air pollutants in the indoor air are also of importance for wellbeing and health. Their levels are influenced both by the outdoor concentrations and the indoor emissions. The increasing use of air conditioning systems in many cases has not resulted in improving the indoor climate but causes a wide range of irritations and health problems summarized as 'sick building syndrome'.
Key words. Indoor climate; thermal comfort; air conditioning.

Introduction

The tropical being 'man' can only survive during the cold seasons of the moderate and cold climate zones by spending most of the time in enclosed spaces with more favorable climatic conditions than outdoors. This is one reason why the first humans of these climate zones lived in caves. Other functions of enclosed spaces are protection against dangers (such as wild animals in earlier days and thieves in modern times), and the provision of privacy.
In industrialized countries today, in general, more than 90% of the time is spent indoors – for sick and old people this figure is close to 100%. Even in the native regions of man, the tropics, people tend to prefer regulated indoor climates once the standard of living reaches a certain level. As sweating is nowadays considered something awkward and hygienically unpleasant, cooling of enclosed spaces is seen as desirable in the hot climate zones.
In our times the ways of influencing the indoor climate are manifold, starting with the choice of building materials and the design of a building, which can include natural systems of heating and cooling as well as active heating, cooling or full air conditioning. This affects not only the thermal parameters of the indoor climate but also the indoor air quality as new pollutants can be emitted from the indoor materials, and the concentration of outdoor pollutants is influenced by the ventilation system.
In discussing the effects of indoor climate on well being, thermal comfort or health, the specific characteristics of the great variety of enclosed spaces like working places, living rooms, sleeping rooms or even public transport, have to be considered. So for example, a climate perfect for an indoor swimming pool would be very uncomfortable in an office or sleeping room.
In the following chapters the relevant climate parameters for wellbeing and comfort in indoor climates are discussed.

Indoor climate parameters

Air temperature

Indoors, the diurnal course of the outdoor air temperature is dampened if not completely suppressed. This is an effect of the heat transfer resistance of the walls, their heat capacity as passive systems, and the active heating or cooling systems.
The air temperature affects the convective heat loss from the body (see paper on heat balance modelling in this review) and the temperature of the expired air[8] (and thus the heat losses for the heating and humidification of the respired air). As the air temperature is only one of the many parameters that affect the thermal state of the human body a so-called 'comfort temperature' cannot be defined in general. In table 1 air temperatures for comfort are listed for different activities and kinds of clothing. The values of the comfort air temperatures are derived from model calculations with MEMI[9] for the heat balance of the body. In making these calculations the other thermophysiological relevant parameters were kept constant (air velocity v and vapor pressure VP) or set equal to the air temperature (mean radiation temperature T_{mrt}). The comfort criterion is that Fanger's[5] comfort mean skin temperature, which is dependent only on metabolic heat production, can be maintained.

Table 1. Comfort air temperatures T_{comf} at different activities and with different kinds of clothing ($v = 0.1$ m/s, $VP = 10$ hPa, $T_{mrt} = T_a$)

Activity	Work Met.	Clothing	T_{comf}
Resting	0 W	0.5 clo	31 °C
	0 W	1.0 clo	29 °C
Standing	43 W	0.5 clo	27 °C
	43 W	1.0 clo	23 °C
Light work	100 W	0.5 clo	22 °C
	100 W	1.0 clo	16 °C
Hard work	200 W	0.5 clo	12 °C

Table 1 shows clearly how important activity and clothing are in terms of the air temperature optimal for comfort conditions. So, for example, in summertime when people tend to wear clothing with a heat transfer resistance around 0.5 clo (short sleeve shirt, light skirt or trousers) the air temperature should be 4 to 6 °C (standing resp. light work) higher than in wintertime with clo values around 1.0. Using this fact in adapting the indoor air temperature rather than keeping air temperatures constant all year long, means that comfort can be maintained and a lot of heating and cooling energy saved.

Humidity

Humidity is certainly the most complex of all climatic parameters important for the assessment of the indoor climate. This is due to the fact that humidity can be expressed in an absolute and a relative way. The most common measures describing the absolute water vapor contents of the air are the dew point temperature (°C) and the water vapor pressure (hPa). The relative humidity (%) is given as the ratio of the actual vapor pressure and the saturation vapor pressure, which is an exponential function of the air temperature. Both the absolute and the relative measures are useful in describing different effects of humidity on the human body. The absolute humidity measures are more appropriate to describe water and energy losses by diffusion through the skin, while the relative humidity is a better measure for the water vapor fluxes from and to the hair of the head. The reason for this difference is that the temperature of the hair of the head is close to the air temperature, while the skin temperature has its own characteristic, due to thermoregulation and the insulating effect of the clothing. The water loss by humidfication of the respired air taken from the mucous membranes of the upper airways is influenced by a mixture of the absolute and relative humidity of the ambient air, since the temperature of the expired air is a function of the temperature of the inspired (ambient) air[8].

The humidity of the ambient air has many effects on the energy and water balance of the body as well as on elasticity, air quality perception, electrostatic charges and the formation of mould[12].

Three different routes of water loss from the body are influenced by the humidity of the ambient air. These are the diffusion of water vapor through the skin (perspiratio insensibilis), the evaporation of sweat from the skin surface, and the humidification of the respired air. In all cases the water is lost in a gaseous form which means an energy loss from the body due to evaporation.

The humidity of the ambient air affects the elasticity of materials and fibres, such as the hair of the head. At low relative humidity only a little water is absorbed to the hair which then feels rough and tends to become brittle. Furniture and carpets are affected in a similar way.

At high humidity levels the air quality tends to be characterized as 'stale' by the occupants of a room. This was proved in a recent study by Berglund and Suppan[4]. Odors are perceived also more intensively when the air is very humid. Part of the effect may be caused by the humidifier and the hygienic conditions of the ducts of the air conditioning system itself, because in many chamber tests high levels of humidity were not natural but created by a humidification system.

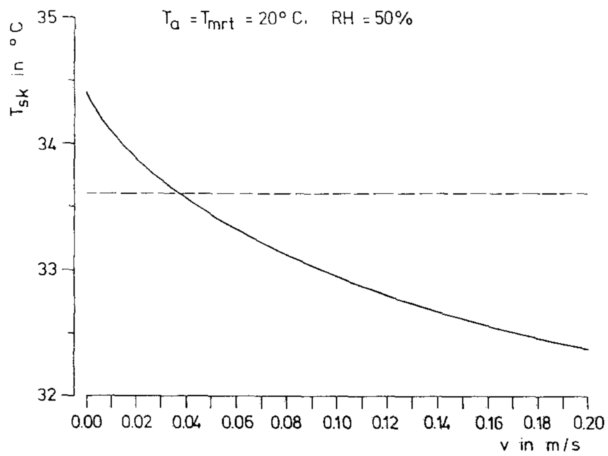
At relative humidities below 40% the probability of electrostatic charging of certain floor covers increases. In particular wall to wall carpets made of artificial fibers tend to become charged. When occupants of such rooms touch conducting materials like the door handle very unpleasant electric shocks are experienced. Sparks generated by electrical discharges can damage integrated circuits of computers and are also a hazard when explosive material is stored in the room.

At high humidities when the dew point temperature of the indoor air reaches the levels of the surface temperature of walls, floor or ceiling, condensation occurs. In general the coldest surface is the external wall of a room. With frequent condensation, the wall becomes soaked and the growth of mould is favored. The spores of mould are known as health hazards to residents. In general, however, the formation of mould can be prevented by adequate thermal insulation of the external wall.

Reviewing the different guidelines and standards for indoor climate it is noticable that there are hardly any fixed recommendations for the humidity of the air. So, for example, in ISO/DIS 7730 for moderate thermal environments[13] only the integral energetic effect of all the climatic parameters is considered in the calculation of the recommended PMV (Predicted Mean Vote) value. No humidity levels are recommended at all. In the ASHRAE Standard[2] the limits for humidity are given in terms of the dew point temperature between 1.7 °C and 16.7 °C. For an air temperature of 20 °C this range would mean relative humidities between 30% and 81%. In the scientific literature there is no general evidence that very low indoor humidities have adverse health effects such as increase in catarrhal diseases.

Air velocity

Besides the air temperature, air velocity is the most important ambient parameter for the convective heat exchange between the human body and the ambient air. The influence of the air velocity on the heat transfer coefficient is not linear but similar to a root function. This means that at very low air velocities small changes in it have a larger effect on the convective heat transfer and by that to the mean skin temperature compared to the same small changes at high air velocities. The importance of the air velocity especially at very low levels



Relationship between the mean skin temperature T_{sk} of a man (35 years, 1.0 clo, sitting, work metabolism 60 W) and the air velocity v; dashed line represents comfort skin temperature.

is shown in the figure, where the mean skin temperature (calculated from the heat balance model MEMI[9]) is shown as a function of the air velocity.

The range of the air velocity displayed in the figure is the common range for enclosed spaces, whereas in naturally ventilated rooms with closed windows it rarely exceeds 0.1 m/s. In artificially ventilated rooms (air conditioned rooms) the air velocity tends to be higher[14,17] and more turbulent. The role of the turbulence of the air current on the heat transfer coefficient is still a matter of scientific discussion but there are indications that high turbulence increases the convective heat loss significantly[6].

The air flow pattern in enclosed spaces can be very complex, depending on the ventilation system (shape of outlets, velocity of fresh air flow) and the building characteristics. So along cold walls or window panes a current of cooling air floating down the walls and into the room along the floor can be induced. This can mean that in spite of a relatively low mean air velocity in a room a sensation of draught may be felt around the ankles. From the physiological point of view air velocities at the very sensitive areas of the neck[16] and ankles are of particular importance.

In addition to convective heat transfer the air velocity also is an important factor in the evaporation of water from the skin and mucous membranes such as the eyes.

Radiation

Two separate radiation spectra are considered in the thermal effects of radiation in biometeorology: the solar spectrum of radiation with wavelengths between 0.3 and 3.0 μm and the terrestrial spectrum between 3 and 100 μm.

In enclosed spaces in general the radiative fluxes of the solar spectrum are of minor importance compared to the thermal radiation in the longer range of wave lengths. But where direct solar radiation is shining through the windows into a room it can mean a high thermal load for the occupants of the room and can heat up the indoor climate. This may be a welcome effect in the cold seasons of the moderate or cold climates. In summertime and the hot climate zones of the earth, however, direct solar irradiance should be avoided by the design of the windows or the application of sun shades.

The thermal radiation of the surfaces (walls, floor, ceiling) is one of the most important ambient parameters for indoor thermal comfort. As shown in the paper on energy balance modelling elsewhere in this review, in typical indoor conditions (no air conditioning) most of the heat produced by the body is lost due to a negative radiation balance. The characteristic ambient parameter for the thermal irradiance of the human body is the mean radiation temperature, which in enclosed spaces without direct solar radiation can be calculated as a weighted mean value of the temperatures of the surrounding surfaces. At typical indoor air velocities (around 0.1 m/s) the thermal effect of raising the mean radiation temperature by 1 K is almost the same as if the air temperature is increased by the same amount. But it is not only the mean radiation temperature that has to be considered in indoor climates. High radiative asymmetries caused by, for example, floor heating, or sitting close to a cold external wall or window, may result in thermal discomfort due to local cooling or heating of the body. In order to avoid these unpleasant asymmetries in the ASHRAE standard[2] a limit for radiative asymmetry is given by a maximum difference of radiation temperatures of 5 K in the vertical and 10 K in the horizontal direction.

Air quality

The indoor air in general contains lower levels of outdoor pollutants such as sulfur dioxide or ozone. On the other hand indoor sources of pollutants like formaldehyde can lead to higher concentrations of these specific substances[18]. The link between the outdoor and indoor concentrations is ventilation. If the ventilation rate is very high accumulation of indoor pollutants can be avoided but at the same time higher concentrations of outdoor pollutants are to be expected indoors. In table 2 the average range of the ratios between the indoor and outdoor concentrations of the most common pollutants is listed. They may differ widely according to the specific outdoor pollution pattern and the indoor emission, especially when smokers are in a room or heaters and stoves are fueled with gas.

In general there is always enough oxygen in the indoor air. During respiration the ratio of the transformed O_2 molecules to the created carbondioxide molecules (respiratory quotient) is close to one, and so the concentration of O_2 decreases by the same amount as the concentration of CO_2 increases. Thus, when a concentration of CO_2 of 0.5% (the threshold concentration for

Table 2. Range of average ratios between indoor and outdoor concentrations of selected inorganic and organic pollutants (Seifert[21]; Ozone: Yokom[25]

Substance	Indoor/Outd. Relation	Comments
Sulfur dioxide	0.1–0.5	incr. with decr. outdoor conc.
Carbon dioxide	1–3	
Carbon monoxide	≤1	without CO-source indoors
	1–5	with CO-source indoors
Nitrogen dioxide	0.5–1	without NO_2-source indoors
	2–5	with NO_2-source indoors
Ozone	0.1–0.25	without O_3-source indoors
Airborne dust	1	without tobacco smoke
	>2	with tobacco smoke
Radon	3–5	
Formaldehyde	10	
Aromat. hydrocarb. (e.g. benzole)	1–3	
Polycyclic aromatic hydrocarbons	0.5	without tobacco smoke
	≥1	with tobacco smoke

working places in many countries) is reached, the O_2 concentration is still at 20.5%. In other words long before there is a risk of too little oxygen in the indoor air there will be a carbon dioxide problem[20]. Therefore the main function of artificial ventilation in rooms with no natural ventilation or many occupants is not to provide enough O_2 but to get rid of the CO_2.

Active systems to change the indoor climate

The first step in providing a comfortable and healthy indoor climate should be taken by the architect of a building choosing the appropriate building materials and construction design for the particular climatic zone. In spite of an optimal building design, in many climatic zones active systems like heating or cooling are necessary for comfort. In rooms with high occupancies or in high rise buildings with no possibility of open windows ventilation systems have to be installed. There is considerable evidence [7,15,22–24] that air conditioning systems do not necessarily provide comfort and wellbeing. Many comparative studies have shown that often the opposite is the case, i.e. the occupants of air conditioned buildings are suffering from the so-called sick building syndrome (SBS).

Questionnaires on problems with indoor climate showed that humidity is the most criticized of all climatic parameters in air conditioned buildings[7,14]. In general humidity is perceived as being too low, even if the air is humidified and the measured values of the relative humidity are higher than 50%.

The SBS is characterized by symptoms such as dryness of mucous membranes, eye irrations, headache, fatigue and increased frequencies of catarrhal disease. Causes for these symptoms are to be found[14,19] in too high and turbulent air velocities, the inability of the individual to influence the climatic conditions, contaminants of the air supplied from the ducts of the humidifier, low frequency noise of the fans, and unphysiological temperature drifts throughout the day. Even the provision of a comfortable thermal environment cannot be achieved as long as there are only thermostats (controlling air temperature) and hygrostats (controlling humidity). The two other important thermal parameters for comfort, radiation and air velocity, are generally still not controlled in air conditioned buildings. As most AC-systems regulate the indoor climate by blowing conditioned air through an inlet of constant diameter into a room, the velocity and the temperature of the supplied air is dominated by the regulatory demands and not by the comfort needs of the people exposed to that air. Therefore at times a draught problem cannot be avoided with the common AC-systems. A solution for this could be the provision of variable air inlets, and partial heating or cooling by radiator panels[3].

The basis for active manipulation of the indoor conditions by heating or cooling systems should be knowledge about the variable thermal preferences depending on the type of clothing and activity. In spite of that, in many air conditioned buildings the setpoints for the indoor air temperature are constant during all seasons causing comfort problems and in addition driving energy consumption to unnecessarily high levels.

Indoor climates can also be affected by changing outdoor conditions[11]. When the ambient air temperature outdoors is decreased by exchanging sealed surfaces for grass with trees and bushes there may be a beneficial effect on the indoor climate especially in the evening when the cool outdoor air is allowed to flow into a room by opening the windows.

Conclusion

As more and more time is spent in enclosed spaces, indoor climate becomes the dominant climate we are exposed to. There are many ways of influencing the indoor conditions but often the integral effects of the multitude of relevant parameters are not considered. This is the basic reason for the high prevalence of dissatisfaction with regulated, especially air conditioned, indoor climates. As long as an integral way of thinking is not the way most air conditioning engineers plan their devices AC-systems should only be installed where they are indispensable. As there are no physiologically relevant integral climate sensors available, the task of controlling the climate should be left to the occupants, who are still the most sensitive climate measuring devices and therefore should have the chance to regulate the climatic conditions individually.

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