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Comfort Requirements in Indoor Climate

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SUMMARY

An analysis of the important factors for comfort in indoor climate is given. For the thermal complex, the results from calculations of the energy balance model MEMI are used to quantify the effects of the single meteorological parameters on occupants in indoor climate. The quantifications show that besides the air temperature, the mean radiation temperature and the air velocity, especially at very low levels, are also quite decisive for the occupant's mean skin temperature which is used as a measure for comfort. An essential requirement to achieve thermally comfortable conditions in a room is the consideration of the heat transfer resistance of the occupants' clothing and their activity level. A short review of other comfort factors, such as lighting, noise and air quality is given. Finally, three international standards for indoor thermal comfort are discussed.

1. INTRODUCTION

One reason for the majority of people to spend most of the time in indoor environments certainly is the more beneficial bioclimate compared to the outdoor conditions. Staying indoors, the occupants are not only sheltered against precipitation and noise but also are exposed to a more constant and more comfortable thermal environment.

This fact already was acknowledged many thousands of years ago, when man lived in caves or similar natural shelters. The building of houses certainly can be ascribed as one of the most important steps of civilisation. In many regions on earth, life is only possible when most of the time can be spent in dwellings. The common characteristic of all these dwellings, which may be igloos, grass huts or houses, is the dampening of the climatic extremes outdoors.

Today, people in industrialized countries spend more than 85% of their lives indoors, and the percentage for the sleeping phase is nearly 100%. Therefore, most of the time, the indoor climate is the dominant factor for thermal comfort and well-being. In central Europe, the majority of people still live and work in naturally climatized buildings. The word 'naturally' in this respect means naturally ventilated with heating facilities for wintertime only. The percentage of people working in air-conditioned buildings, however, is increasing steadily, e.g., now reaching 5% [13] in Western Germany. There are many problems arising from artificial air conditioning, which may cause discomfort in many ways. In this paper, however, the more basic aspects of thermal comfort in indoor climate are dealt with.

Research in thermal comfort and the application of the results becomes increasingly important as more and more people do not have the chance to create their individual comfort conditions anymore. Thermal comfort on the other hand is a necessary basis for well-being, health and work efficiency.

Before the single parameters of the indoor climate and their effects on comfort can be discussed, the definition of 'comfort' has to be given. According to the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) [1], thermal comfort means 'the condition of mind which expresses satisfaction with the thermal environment'. So, for example, a thermally comfortable person would neither desire warmer nor cooler conditions if asked. The word 'comfort' in general comprises much more than only thermal aspects. In order to feel comfortable, besides social and psychological influences which cannot be dealt

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with here, noise, lighting, and air quality are of importance, too.

2. THERMAL COMFORT

2.1. Physiology of thermal comfort

Man does not have any specific sensors for air temperature, thermal radiation or humidity. The only way to perceive the ambient climate are the impulses by the cold and warm receptors in the lower skin layer. In other words, man only can perceive the effects of the ambient climate by his skin temperature and its changes. The skin temperature on the other hand is affected by all of the so-called thermal climatic parameters, i.e., air temperature, air humidity, air velocity and radiation temperatures. According to results of thermal physiology, the skin temperature is a proper indicator for the thermal sensation of the ambient climate. Thermal comfort on the other hand is a more integral unity and represents the complete thermal state of the body. Therefore, in addition to the mean skin temperature, sweat rate, skin wettedness or the core temperature are also characteristic parameters for describing thermal comfort. Especially in transient conditions, thermal sensation and comfort might deviate. For example, somebody having left a sauna and taking a cold shower will have the sensation 'cold' but at this moment will feel thermally 'comfortable'.

Assessing the climate in a physiologically relevant way, it is necessary to use an energy balance model of the human body considering all climatic parameters. One of the most popular models is the so-called 'comfort equation' of Fanger [5], who uses comfort values of the mean skin temperature and the sweat rate in his energy balance calculations. Because of these assumptions by his model, though being a steady state model, fictive thermal loads of the body are calculated, which by empirical functions can be transferred to the predicted mean vote (PMV) or predicted percentage of dissatisfied (PPD) indices. Fanger's indices have become very widespread and are part of many standards for indoor climate. Where it is desired to calculate actual values of the energy fluxes and the resulting body temperatures, one has

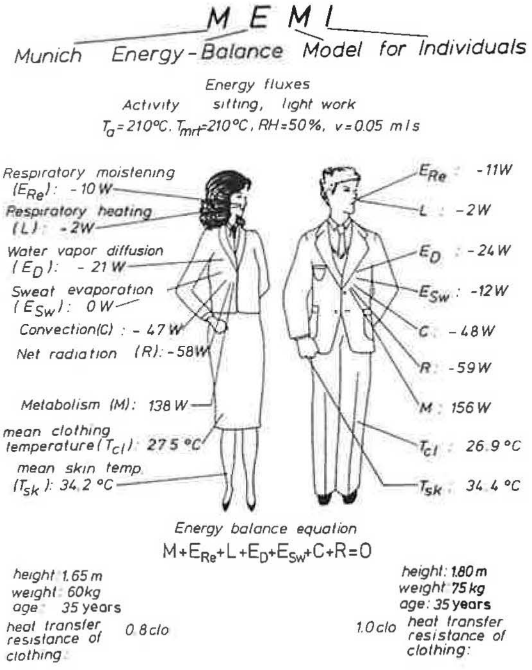

Fig. 1. Energy fluxes of a woman and a man for typical indoor conditions.

to apply a model like the Munich Energy balance Model for Individuals (MEMI) [9], which is a two-node model consisting of three equations and therefore not needing any assumptions for the skin temperature or sweat rate. MEMI therefore can be used to make a detailed diagnosis of the effects of a given climate on the body parameters of a subject. In the following chapters, the effects and the importance of the climatic parameters are discussed with respect to the results of calculations with MEMI. In order to give an impression of the heat exchange characteristics for indoor conditions, in Fig. 1 the heat fluxes of a man and a woman are given quantitatively. This Figure clearly shows that most of the heat produced by metabolism is lost by radiation. The convective heat loss only ranges at the second position.

2.2. Important parameters for thermal comfort

Generally in human biometeorology, the air temperature, humidity, air velocity and mean radiation temperature are regarded as the thermally relevant measures. All of them influence the heat exchange of man with the environment and therefore are important for thermal comfort. The mean radiation temperature is a measure for the radiative fluxes from the surrounding surfaces, i.e., walls, windows, floor and ceiling. Its value, which is given, for example, for a temperature in °C, corresponds to the uniform surface temperature of a black body enclosure (emission coefficient = 1), at which the same radiative heat gain or loss occurs as in the actual case. If there is no direct solar radiation coming in through a window, the mean radiation temperature can be calculated as the weighted mean value of the surface temperatures of the walls, windows, floor and ceiling. In the case of direct solar irradiation, the mean radiation temperature is essentially higher.

The only parameter which is regulated in traditional rooms is the air temperature; in air-conditioned buildings the humidity also can be regulated. The mean radiation temperature and the air velocity, however, are not even measured and therefore cannot be considered when regulating the climate. In air-conditioned buildings, even the air velocity is often governed by the needed exchange of air in order to meet the thermal demands.

In the following chapters, the sensitivity levels of the single parameters important for thermal comfort are discussed. As one measure for comfort, the mean skin temperatures T_{sk} of a model man in a steady state are used. They were calculated with MEMI [9] for a 35-year-old man who is sitting and doing light work (metabolic rate 146 W) wearing a business suit with a shirt and a waistcoat (1.0 clo). As a comfort reference the comfort mean skin temperature after Fanger [5] is displayed in Figs. 2 - 4 and 7 (dashed line). At warm conditions, when sweating is necessary to keep the energetic balance, skin wettedness has to be considered as an important factor for comfort too [2]. As a rough threshold, skin wettedness values transgressing 25% are to be expected to cause discomfort [6].

2.2.1. *Air temperature*

In general, the air temperature is regarded undoubtedly as the most important parameter of the indoor climate and therefore is measured in many places. In Fig. 2 the dependence of the mean skin temperature of the model man T_{sk} on the air temperature T_a is shown. At these calculations the mean radiation temperature, relative humidity and air velocity were kept constant.

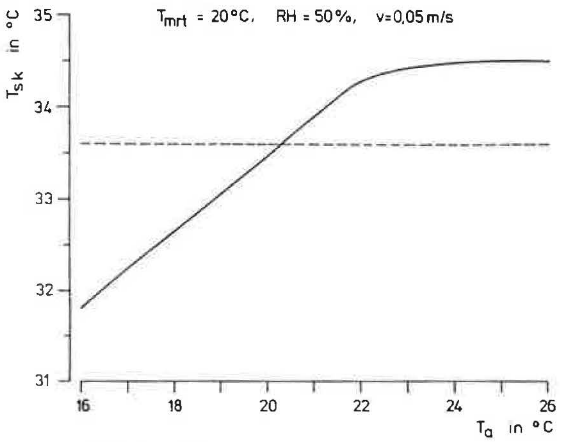

Fig. 2. Relationship between the mean skin temperature T_{sk} of a man (35 years, 1.0 clo, sitting, work metabolism 60 W) and the air temperature T_a.

Figure 2 shows a steep increase of the mean skin temperature T_{sk} with increasing air temperatures up to values of about T_a = 21 °C. Then transpiration starts, which leads to a dampening of the increase of the skin temperature. The comfort skin temperature is reached at an air temperature of a little more than 20 °C. At this light activity the skin wettedness does not exceed 4% at an air temperature of T_a = 26 °C.

2.2.2. *The mean radiation temperature*

The course of the mean skin temperature T_{sk} as a function of the mean radiation temperature T_{mrt}, shown in Fig. 3, is almost

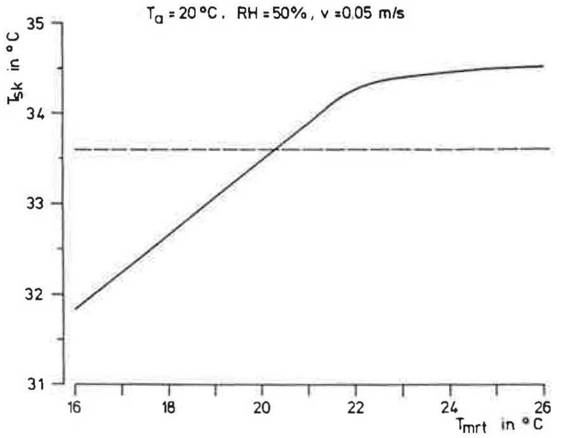

Fig. 3. Relationship between the mean skin temperature T_{sk} of a man (35 years, 1.0 clo, sitting, work metabolism 60 W) and the mean radiation temperature T_{mrt}.

congruent to Fig. 2 for the air temperature T_a. At very low air velocities ($v = 0.05$ m/s), e.g., in naturally ventilated rooms, the change of the mean radiation temperature T_{mrt} by 1 K almost has the same effect on the heat budget of man as the change of the air temperature T_a by 1 K. As a consequence, both parameters have the same weight for thermal comfort in the situation simulated here. At higher air velocities, the influence of the air temperature T_a compared to that of the mean radiation temperature T_{mrt} increases due to the increasing convective heat transfer coefficient. So, for example, the change of T_a by 1.0 K can be compensated by an opposite change of T_{mrt} by 1.1 K at an air velocity of 0.10 m/s, and by 1.4 K at an air velocity of 0.20 m/s.

2.2.3. *Air velocity*

In Fig. 4 the dependence of the mean skin temperature T_{sk} on the air velocity v is shown. The Figure reveals that especially in the range of very low air velocities a strong influence on the mean skin temperature can be expected. According to the standard DIN 1946 [4] for indoor climate, at an air temperature of 20 °C air velocities up to 0.1 m/s are permitted. In many cases, however, even this high value is exceeded in air-conditioned rooms [13].

Some recent investigations by Mayer [15], which still have to be regarded as pilot investigations, revealed that besides considering the mean air velocity, the turbulence of the air flow has a great influence on the heat exchange from man to the ambient air. By measurements of the heat transfer coefficient from an artificial head, Mayer [15] found that the heat transfer coefficient can be described as a function of the mean air velocity and the standard deviation of the air velocity. The only way to measure these turbulent fluctuations is to use hot wire probes.

In Fig. 5 the dependence of the mean skin temperature T_{sk} on different degrees of turbulence Tu of the air flow at a constant mean air velocity of $v = 0.10$ m/s is simulated. There is quite an effect on the mean skin temperature even when the mean air velocity is constant.

Another way of displaying the potential thermal effects of air turbulence is shown in Fig. 6. Here instead of the mean skin temperature T_{sk} a so-called comfort temperature

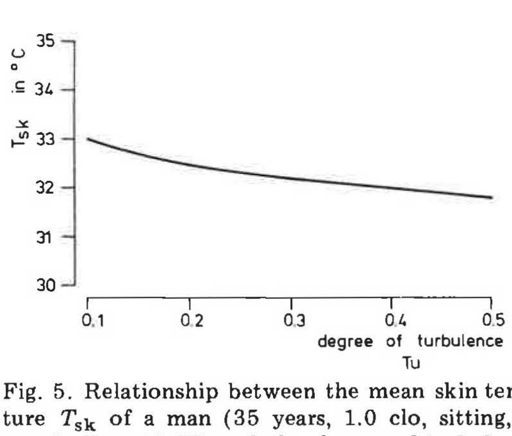

Fig. 5. Relationship between the mean skin temperature T_{sk} of a man (35 years, 1.0 clo, sitting, work metabolism 60 W) and the degree of turbulence Tu [$Tu = (v(84\%) - v(50\%))/v(50\%)$].

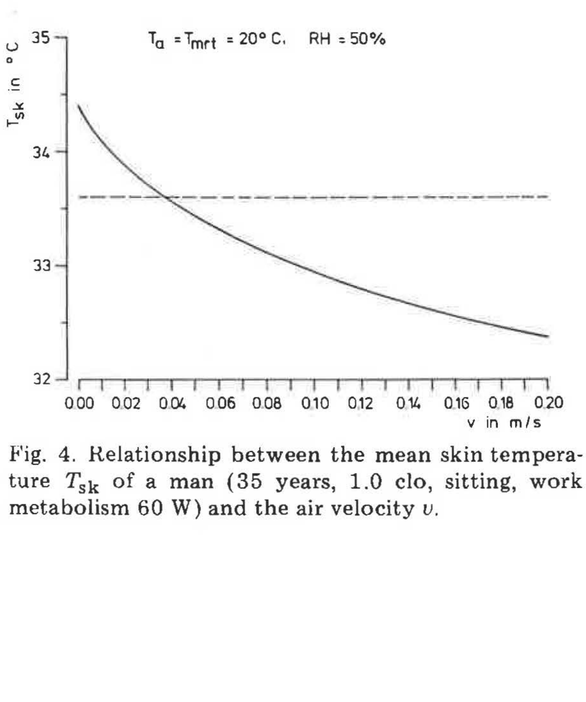

Fig. 4. Relationship between the mean skin temperature T_{sk} of a man (35 years, 1.0 clo, sitting, work metabolism 60 W) and the air velocity v.

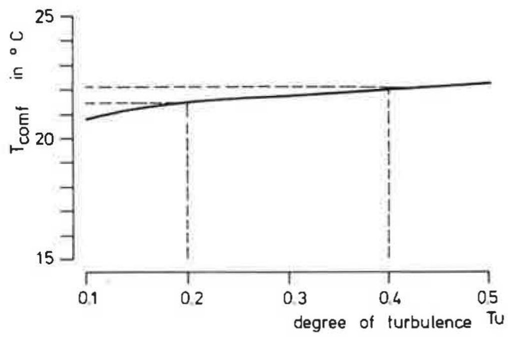

Fig. 6. Relationship between the mean comfort temperature T_{comf} of a man (35 years, 1.0 clo, sitting, work metabolism 60 W) and the degree of turbulence Tu [$Tu = (v(84\%) - v(50\%))/v(50\%)$].

T_{comf} is given as a function of the air turbulence Tu. The comfort temperature T_{comf} is defined as the air temperature at which the comfort skin temperature (after Fanger [5]) is reached. In the calculations of T_{comf} the mean radiation temperature T_{mrt} is set equal always to the air temperature T_a, the air velocity v is set to 0.10 m/s, and the vapour pressure is set to 11.7 hPa (RH = 50% at T_a = 20 °C). Figure 5 clearly shows that T_{comf} increases with increasing air turbulence Tu. The difference between Tu = 0.2 (representative for naturally ventilated rooms) and Tu = 0.4 (found in air-conditioned rooms) [15] approximately amounts to 0.6 K. This fact opens a wide field of necessary future investigations, which should be considered at the definitions of revised standards.

2.2.4. *Humidity of the ambient air*

The most popular measure for the humidity of the ambient air is the relative humidity. This measure is physiologically relevant for the exchange of water vapour at surfaces which have a temperature close to the air temperature (e.g. hair). For water vapour exchanges at surfaces which have almost constant temperatures or which are not governed by the air temperature alone, the absolute water vapour contents of the ambient air is the relevant measure. Such absolute humidity measures for example are vapour pressure, dew temperature or specific humidity. As most recommendations for indoor thermal comfort are based on the relative humidity (RH), the effects of changes of this parameter are displayed in Fig. 7: RH is shown between 30% and 70% which can be regarded as the expected natural range. From Fig. 7 it becomes obvious that the role of the relative humidity in indoor climate is of a minor degree compared to other factors of the thermal complex discussed already.

Besides the energy point of view, low values of the humidity of the ambient air might have negative effects on the mucous membranes of the upper respiratory tract, which might dry out and thereby lose their protective function against infections. Also, the skin and hair at low humidity values become dry and rough. Other side effects of too low relative humidity are electrostatic charges of floor coverings. Too high humidity levels,

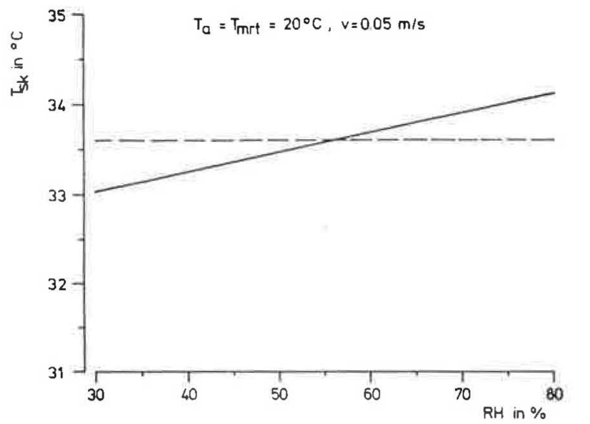

Fig. 7. Relationship between the mean skin temperature T_{sk} of a man (35 years, 1.0 clo, sitting, work metabolism 60 W) and the relative humidity RH.

on the other hand, may cause condensation at cool external walls, moistening of the wall material and the formation of mould.

In general, owing to the reasons mentioned above, a range of relative humidity between 30% and 70% is recommended. According to this recommendation, humidification of the indoor air would be sensible, if at all, only at outdoor temperatures of less than 0 °C.

2.2.5. *Asymmetric radiation and temperature fields*

Besides the parameters mean air temperature T_a and mean radiation temperature T_{mrt} which are considered in Figs. 1 and 2, their spatial distribution can be relevant also for comfort. So, for example, a highly asymmetric radiation field (e.g., cool window, cool external wall or direct solar irradiation) might lead to discomfort even when the mean radiation temperature lies within the comfort zone. A secondary source of complaints due to radiative asymmetries may arise from draughts near cold walls, where the cooling air is flowing down these walls and inducing a horizontal flow of cool air close to the floor directed into the room.

Also, an inversion of the natural vertical indoor temperature gradient (normally temperatures increase from the floor to the ceiling), for example, caused by floor heating, can have negative effects leading to pathological symptoms. Marmasse [14] reported complaints from people working or living in rooms with floor heating. In the very warm foot area, a diffuse blood accumulation in the veins of the legs occurred by vasodilatation.

Also, too high differences between air temperature and mean radiation temperature should be avoided. Grandjean [7] recommends a maximal deviation of the mean radiation temperature from the air temperature by not more than 3 K.

2.2.6. *Activity and clothing*

Besides the meteorological parameters, personal characteristics like age, weight, height, sex, activity and clothing are decisive also for thermal comfort. The two most important of these personal parameters are activity and clothing. According to his activity, man produces variable amounts of internal heat by metabolism. For every kind of activity, a so-called typical work metabolism has to be added to the basal metabolism (e.g., 86 W for the young man) in order to get the total heat production of the body. The range of the work metabolism lies between 0 W for sleep and approximately 1000 W for very hard work or intensive sport. Because of this wide range the influence of the activity on the comfort requirements is very high. In Fig. 8 the comfort temperature T_{comf} is shown as a function of the work metabolism. There is a clear decrease of T_{comf} with increasing work metabolism. So for example $T_{comf} = 29.4$ °C for sleep. At a work metabolism of 40 W (e.g., standing without moving) it decreases to $T_{comf} = 24.6$ °C and at a work metabolism of 100 W (office work) $T_{comf} = 17.4$ °C.

For a specific climate, like the given indoor climate, there is a threshold of the activity at which the skin wettedness reaches 100% (total surface wetted by sweat). A further increase of the activity would demand more sweat evaporation which is not possible anymore. Therefore steady state cannot be maintained for higher activities and over a longer period there would be the risk of circulatory disorders. In Fig. 9 the skin wettedness w is shown as a function of the work metabolism. For the given climatic scenario for $M_{work} < 60$ W, the skin stays dry. The threshold value of $w = 100\%$ is reached at $M_{work} = 360$ W. Certainly it has to be mentioned that all calculations were done for sedentary subjects. Vigorous communal activities are connected with body motion and thereby with a higher relative air velocity. Therefore the actual threshold value for activities is higher than shown in Fig. 9.

A really efficient way to regulate the heat exchange of the body is by means of the proper kind of clothing. In Fig. 10, the

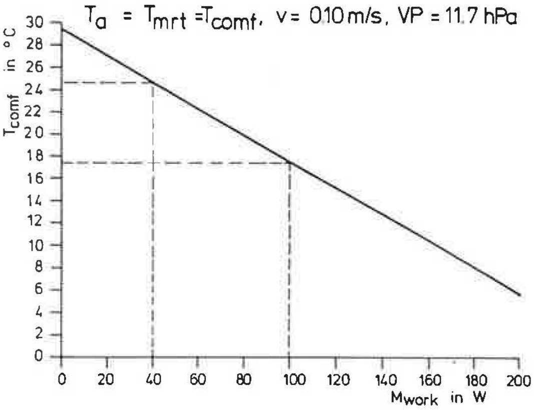

Fig. 8. Relationship between the comfort temperature T_{comf} of a man (35 years, 1.0 clo, sitting, work metabolism 60 W) and the work metabolism M_{work}.

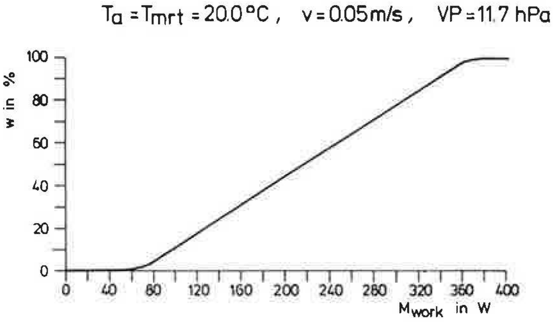

Fig. 9. Relationship between the skin wettedness w of a man (35 years, 1.0 clo, sitting, work metabolism 60 W) and the work metabolism M_{work}.

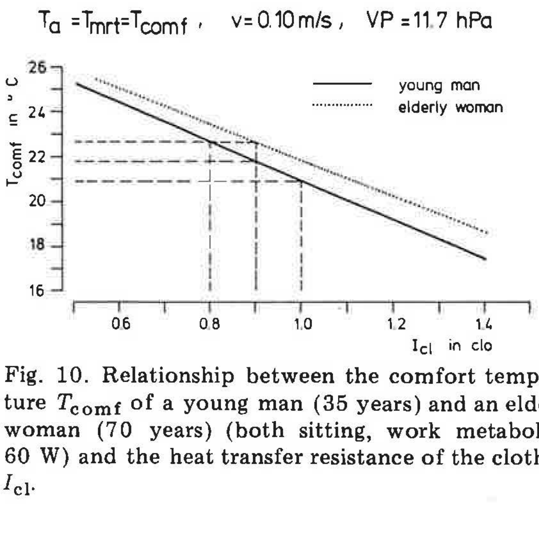

Fig. 10. Relationship between the comfort temperature T_{comf} of a young man (35 years) and an elderly woman (70 years) (both sitting, work metabolism 60 W) and the heat transfer resistance of the clothing I_{cl}.

comfort temperature T_{comf} is shown to be dependent on the heat transfer resistance of clothing I_{cl} in the range from 0.5 clo (light summer clothing), over 1.0 clo (typical business suit with waistcoat) to 1.5 clo (business suit + cotton coat). T_{comf} is very sensitive to changes of I_{cl}. While the young man feels comfortable at $T_{comf} = 25.2$ °C wearing summer clothing ($I_{cl} = 0.5$ clo) he would prefer a comfort temperature of $T_{comf} = 20.9$ °C wearing a business suit with waistcoat. Figure 10 also shows differences in the preferred climatic conditions between subjects of different age and sex due to differences in metabolism. The elderly lady (dotted line) would like to have warmer conditions or to wear clothing with higher heat resistance values compared to the young man in order to feel comfortable. The difference in T_{comf} between these two subjects amounts to about 1 K.

The results of Fig. 10 are quite important for understanding the thermal requirements for comfort. As the choice of clothing, in general, is governed to a high degree by the season and the expected weather situation, the indoor climate has to be adjusted to this fact. A constant yearly indoor climate, therefore, will hardly meet the comfort demands of people being exposed to it.

3. LIGHT AND NOISE

Basically, the light intensity in a room should be adjusted so that for a specific activity it is high enough without tiring the eyes. On the other hand, too high light intensities can be harmful in the long term, according to Hollwich and Dickhues [10], causing hormonal disorders similar to stress.

In general, light intensities of 300 - 1000 lux are necessary for manual work. The light sources should be mounted so that a light field with much contrast is assured. Investigations by Höfling [8] showed that diffuse room lighting by neon lights mounted on the ceiling frequently caused headaches, eye strain and fatigue. In order to avoid these complaints, the use of additional table lights directly at the working places proved to be successful.

Where the choice of wall colours is concerned, not only psychological aspects have to be considered. In order to avoid dazzle by reflected light, according to Höfling [8], the reflectivity of the walls should not exceed 50%, which can be reached approximately with a yellow-beige paint.

In the assessment of noise in indoor environments, certainly the general statement is valid, that high levels of noise over a long period cause disturbances of well-being, dizziness and decreased concentration. This obviously is also valid for low frequency noise with frequencies between 25 and 100 Hz, at the lower threshold of audibility [13]. Noise of these frequencies often is produced by air-conditioning systems or generators and other machines.

4. AIR QUALITY

In general, indoor air contains enough oxygen for respiration. When speaking about 'bad' air, therefore, it is not the lack of oxygen or any other constituent which is implied, but the presence of gases or odours which originate from the occupants, furniture, wall and floor materials or from outdoors. In badly ventilated rooms with many occupants it may happen that CO_2 concentrations reach values which can cause fatigue. In regions with high outdoor pollution, the indoor air is cleaner than the outdoor air, especially as far as the aerosol concentration is concerned. Therefore on days with a smog alarm, people are advised to keep their windows closed.

A problem which is very hard to quantify is discomfort caused by odours. For example, often the air is characterized as musty, without knowing the causes for this statement. Even in air-conditioned buildings with a measurable optimal air quality, complaints about odours are frequent. There still is a lot of research work to do in this field.

5. STANDARDS FOR INDOOR COMFORT

In order to assure a comfortable climate, especially for working people, standards have been developed as guidelines for the regulation of air-conditioning systems as well as for architects and air-conditioning engineers. Some of these standards have become very popular and acknowledged on an international basis. As the new COMECON standard [12] will be discussed in a separate paper in this journal, only the general characteristics of this standard are described.

Briefly, the COMECON standard defines comfort zones by giving optimal and admissible climatic parameters deduced from empirical charts. As the main climatic parameter the globe temperature is taken. Vertical and horizontal gradients of the globe temperature, radiant asymmetries as well as personal parameters like activity and clothing are considered.

Another standard which is most popular in the U.S.A. is the ASHRAE Standard 55 [1]. This standard is revised at intervals of five years. The ASHRAE standard tries to define comfort zones in which 80% or more of the occupants will characterize the environment as thermally acceptable. The threshold values are the results of intensive experimental work and questionnaires of subjects in climatic chambers. The most important parameter characterizing the climatic conditions of the ASHRAE standard is the operative temperature T_o. T_o is defined as 'the uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation and convection as in the actual non-uniform environment'. By considering both the radiant and the convective heat fluxes T_o is similar to the globe temperature. By means of comfort charts for a variety of different climatic conditions, activities and clothing ensembles, comfort zones can be derived. In the ASHRAE standard, also, threshold values for dew point temperature, air movement, temperature drifts, vertical temperature gradients and radiant asymmetry are given.

A more mathematically and physically oriented standard is the standard of the International Organisation for Standardization (ISO/DIS 7730) [11] for moderate thermal environments, which is quite popular in Europe. This ISO standard is based on the comfort equation of Fanger [5] defining comfort zones for a 'predicted percentage of dissatisfied, PPD' of lower than 10% which corresponds to a 'predicted mean vote, PMV' of $-0.5 < \text{PMV} < +0.5$. By the comfort equation of Fanger [5] all possible combinations of the climatic and personal parameters can be evaluated and a comfort statement can be made. In addition to the mathematical approach, nomograms are given also in the ISO standard. In these nomograms and tables the operative temperature T_o, as in the ASHRAE standard, is used as the main climatic parameter. Besides the international standards there are many national standards, e.g., the DIN 1946 [4].

Standards alone are not sufficient to assure comfortable conditions. Proper measuring equipment to quantify the most important climatic parameters is fundamental. The oldest of the more complex instruments is the globe thermometer. A further development is the ellipsoidal sensor of the Comfy-Test or the cylindrical sensor of Brown and Gillespie [3], introduced recently.

Today biometeorological research provides us with the information necessary to achieve indoor thermal comfort. But still there is a wide gap between these results and their application. This gap only can be closed by the acceptance of these results by architects and air-conditioning engineers.

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