DESIGN AND ASSESSMENT OF INDOOR ENVIRONMENT

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ABSTRACT

This paper reflects the research presented in session 1 "Indoor Environment" of the present CLIMA 2000 Congress. Design and assessment of the indoor environment, mainly its thermal component, is discussed. The steps of the design process as well as the model prediction and the field assessment of the indoor environment are included in the discussion. Special attention is paid to the correct application of the requirements specified in the present indoor climate standards. Examples from research presented at this congress are used. It is concluded that a high quality indoor environment can be achieved only when good design is followed by proper maintenance and use of the HVAC system. Design engineers, architects, managers and occupants play an important role and are responsible parties in this process. They all need to be involved in the dissemination of the available up-to-date knowledge concerning the indoor environment.

INTRODUCTION

People spend a large part of their daily life indoors. It is therefore essential that buildings are designed to be pleasant and comfortable for human beings without posing any health risks. Heating, ventilating and air-conditioning (HVAC) systems are one of the main components of building design. They are aimed to provide occupants with good air quality and a comfortable thermal environment. The challenge for engineers and architects is to provide occupants with a comfortable indoor environment while keeping energy costs at a low level.

Recommendations and requirements for a comfortable indoor environment have been developed over the years and are included in the present standards. However, despite the availability and public-domain status, very often the recommendations are not followed, or they are incorrectly followed, when HVAC systems are designed. The result is an increasing number of complaints from occupants, and very often increased energy consumption.

The design of an indoor environment has many aspects (Clements-Croome, 1997). In this paper the design of an acceptable indoor environment and its assessment is discussed in relation to the research work presented in the papers included in the session "Indoor Environment" of this congress. The design of the thermal component of the indoor environment is the main topic of discussion because most of the papers in the section are related to this subject. The discussion is restricted to the design of office-type spaces. Only limited discussion of visual and olfactory components of the design are included. The interaction of the thermal, olfactory, visual and acoustic components of the indoor environment is discussed briefly.

DESIGN OF AN ACCEPTABLE THERMAL ENVIRONMENT

Design steps

A HVAC system must be designed to provide an acceptable indoor environment, and in particular a thermal environment in a room according to the requirements specified in the indoor climate standards. It should be remembered however, that this is only the first step towards the design of a high quality thermal environment that is acceptable for a large number of the occupants, because of the following reasons:

- The requirements specified in the standards are based on experiments with a large group of people and represent occupants' average thermal sensation. The requirements do not take into account large individual differences between the occupants in their thermal sensation, clothing insulation and metabolic rate. The preferred temperature of individual occupants may differ up to 10 K, with a standard deviation of □2.6 K (Wyon 1996). The clothing insulation and design may also differ significantly. The metabolic rate during stressful work can be significantly higher due to muscle tension. Field studies with a sufficiently large number of reviewed occupants confirmed the validity of the requirements in the standards. However, in many offices the number of occupants is small and due to individual differences, the indoor environment established according to the standards may not be that preferred by the occupants.

- The thermal comfort requirements specified in the present standards and the models of human response are meant to be used to estimate an acceptable range of environmental parameters during the design of the building, when the future occupants are unknown. Furthermore, the activity of the occupants in the rooms for which the HVAC is designed may change over time.

- The requirements for local thermal discomfort in the standards and the models for predicting occupants' thermal sensation are the result of laboratory experiments where people were exposed to one local thermal discomfort at a time. Furthermore, during the laboratory experiments, subjects were in thermal neutrality or close to thermal neutrality. In practice, however, occupants are often exposed to two or more types of local discomfort, for example draught and radiant temperature asymmetry caused by cold windows. Also, occupants are not always in thermal neutrality for the body as a whole.

- Very often in practice occupants have to compromise between different components of the indoor environment. For example in rooms with a poor ventilation, occupants have often to compromise between thermal comfort and air quality and in the summer between the better air quality of the outdoor air provided through open windows and disturbing outdoor noise. This compromise is different for each occupant and also differs in time.

The second important step is to design a HVAC system that allows for adjustments of the thermal environment in the occupied zone of rooms (at least the air temperature) within the ranges specified in the standards in order to suit a group of occupants. It is possible that the occupants in one room prefer a higher or lower air temperature than the occupants in another room. The design of the indoor environment should consider the more sensitive people. Draught, defined as unwanted local cooling caused by air movement, is one example of the most common complaints in practice. Some people are extremely sensitive, while others are insensitive to air movements. It is much more difficult in practice to compensate for air velocities that are too high than to provide additional air movement (by desk fans for example). The HVAC system should also allow for adaptation of the thermal environment, as often the same rooms are used by different occupants and for different purposes spread over the time of occupancy.

The third step in the design process is to provide a comfortable indoor environment for each individual occupant. This means that it should be possible for each occupant to adjust to some extent his/her own thermal environment. Present technical development enables the most sensitive occupants, as well as occupants performing work involving different activities at the same time, to adjust for comfort by means of inexpensive and common devices such as local heaters, desk fans, etc. at their workplace.

New thermal comfort indices?

Man's thermal neutrality and comfort depends on four environmental parameters (air temperature, mean radiant temperature, air velocity and relative humidity) and two personal factors (clothing insulation and activity level). Thermal comfort may be achieved by using many different combinations of the above variables. Therefore HVAC engineers can apply fundamentally different technical systems that will provide thermal comfort for the occupants. In all cases, thermal comfort is the "product" which is produced and sold to the customer by the heating and air-conditioning industry. It is therefore obvious that quantitatively expressed comfort conditions are of great importance.

Comfort indices for design and evaluation of the indoor thermal environment have been developed over the years (ASHRAE Handbook Fundamentals 1993). The main idea behind the indices is to predict man's thermal comfort. With given personal factors and environmental parameters, the indices may predict whether the indoor thermal environment is acceptable or not for the occupants. For normal daily conditions the indices most used are the PMV-PPD indices developed by Fanger (1972), and the SET^* (ET^*) index developed by Gagge et al. (1971). The indices are based on results from experiments with large numbers of subjects and have been validated over the years. Yet new studies on further development of indices for indoor environment assessment are being performed. Two of them, by Mochida et al. (1997) and by Kubota et al. (1997), are reported at this congress. Mochida et al. (1997) questions the validity of the skin wettedness assumptions used for the development of the ET^* index. The results from their experiments with human subjects show that even at constant average skin temperature the skin wettedness varies depending on the humidity and the temperature of the environment. The experimental results are used to modify and develop further the psychometric chart by adding a line of constant skin temperature of 36°C on which the skin wettedness changes from a maximum of 0.8 to a minimum of 0.35. The findings will help to achieve more accurate design of the indoor thermal environment. However, further research is needed because the results of this study are based on experiments with only two male subjects, thus ignoring the large individual differences between people.

An assumption for a linear relation between the sweating rate and the mean skin temperature is analysed by Kubota et al. (1997) and an index PMST (Predicted Mean Skin Temperature) is suggested for assessing of indoor thermal environment. The analyses are extended to the prediction of the mean skin temperature of people during transients, when moving from a warmer to a cooler thermal environment. It is questionable, however, whether the mean skin temperature can be used as an index under non-steady-state conditions. Results from a study reported by Knudsen and Fanger (1990) for example, reveal that step-change in operative temperature is felt by people instantantly while their physiological response (i.e. mean skin temperature) reaches steady-state level after a much longer time. Furthermore, at comfortable temperatures, human response to temperature step-changes upwards and downwards is different. After an operative temperature up-step, the new steady-state thermal sensation is experienced immediately, while in the case of down-steps, the thermal sensation drops immediately to a level cooler than the later steady-state sensation reached within 30 minutes.

Are all environmental factors considered in the present standards?

The PMV-PPD indices are included in ISO standard 7730 (1994), which has recently been approved as European standard, EN ISO 27730 (1995) and ET^* index used by ASHRAE (ASHRAE Standard 55 1992, ASHRAE Handbook of Fundamentals 1993). The PMV index (PMV for Predicted Mean Vote) predicts the average thermal sensation of a large group of people. A PMV=0 will be equivalent to thermal neutrality. The quality of the thermal environment may be expressed by the PPD index (PPD for Predicted Percent Dissatisfied) which is related to the PMV value. For PMV=0, PPD will be equal to 5%, i.e. 5% of the occupants will be dissatisfied with the thermal environment. A PMV=±0.5 will correspond to 10% dissatisfied.

A person may feel thermally neutral for the body as a whole (general thermal comfort), but may not be comfortable if one part of the body is warm and another cold. It is therefore an important requirement for thermal comfort that no local warm or cold discomfort exists on any part of the human body. Such local discomfort may be caused by an asymmetric radiant field, by local convective cooling (draught), by contact with a warm or cold floor, or by vertical air temperature gradient.

Draught is one of the most common complaints in practice, especially for occupants performing work at a low activity level. Draught may cause people to stop ventilation systems. The occupants may try to counteract the draught by elevating the air temperature and during the winter this will normally increase energy consumption.

In a calm, comfortable environment there is a free convection air movement around the human body. This air movement can carry contaminants from the floor to the breathing level. The free convection air movement interacts with the room air motion. This interaction plays a critical role for the transportation of contaminants to the human respiratory system and from person to person. The local air motion around the human body has a significant importance for the heat and moisture transport from the body. The occupant sensation of draught depends on the interaction of the two airflows.

Present international standards (ISO 7730 1994, EN ISO 27730 1995 and ASHRAE 55 1992) as well as several national standards (DIN 1946 1994, DS 474 1995) require draught assessment based on air temperature, mean velocity and turbulence intensity of the airflow in rooms. Mean velocity is defined by the instantaneous velocity averaged over an interval of time while the turbulence intensity is defined by the standard deviation of velocity divided by the mean velocity. Yet new findings about human response to air movement are presented at this congress by Toftum et al. (1997). The impact of the airflow direction on occupants’ discomfort due to draught has been studied and reported. The results of this study, based on human subject experiments at several combinations of air temperature, velocity and airflow direction, show that airflow direction has a significant impact on occupants’ sensation of draught. Previous research reported by Mayer and Schwab (1988) shows that the neck is more sensitive to air movement than the face. Further, more subjects complain of draught on the face with upward than with downward flows. These show that the airflow direction in rooms has to be considered very carefully, along with air temperature, mean velocity and turbulence intensity of the airflow, during design of the indoor thermal environment. These results are of practical importance. The air distribution, i.e. airflow direction, in spaces depends on the ventilation system and the interior of the space. At present, fresh air is provided to spaces through air supply devices located on the ceiling, at the walls, on the floor or on the desk in front of the occupants. Different parts of the human body may be exposed to air movement from different directions.

What is next research?

Comprehensive research on thermal comfort has been performed during the last several decades. But still quite a lot needs to be done. The requirements in the standards are based on experiments with human subjects at thermally neutral conditions. However very often occupants are exposed to a slightly cool or warm environment. Human response to local discomfort at such conditions will be different and needs to be studied. The requirements for local discomfort in the standards are from laboratory experiments when human subjects were exposed to only one type of local discomfort at the time, for example, draught, vertical temperature difference or radiant temperature asymmetry. In practice it is often that occupants are exposed to more than one local discomfort at the time. For example in rooms with displacement ventilation occupants may experience discomfort due to draught at the feet and vertical temperature difference at the same time. Human response to simultaneous effects of two or more types of local discomfort need to be studied. Most of the research on thermal comfort has so far concentrated on steady-state conditions. However, in buildings in practice the thermal parameters or the occupants’ clothing and activity may change during the day thus affecting his/her perception of the thermal environment. More research is needed to describe human response to transient conditions.

Indoor air quality

Indoor air quality in residential and non-industrial working environments has received growing attention over the past 20 years from the scientific community. Field studies have documented a strong correlation between occupants' complaints and poor indoor air quality. Indoor air quality research has covered identification of pollution sources, improvement of ventilation effectiveness, modelling of human response, etc. It has been acknowledged that not only occupants but also the building, the furnishing, the HVAC system, etc. contribute to the air pollution in a space. New units, olf and decipol, have been introduced to quantify the way in which air is perceived by human beings (Fanger 1988). Olf is a unit which quantifies the source strength of air pollution; decipol is a unit quantifying perceived air pollution. Intensive work is performed on the development of international and national standards on indoor air quality (draft ASHRAE Standard 62 1996, European pre-standard prENV 1752 1997, etc.,). There is an urgent need for these standards. Even though not yet approved, they have already been used for the design of buildings. At this congress, Nouwynck (1997) reports on the design of a school in Brussels based on the European pre-standard prENV 1752 (1997). Having completed the initial design, he concludes that "when applied for a low polluting building, the standard leads to realistic values of required ventilation rates and the "olf-decipol" method enables designers to calculate either ventilation rate or comfort category in different and specific situations". However, problems are identified as well. They are related to difficulties of measurement of the sensory pollution load from building materials, construction and maintenance of HVAC systems, etc.

Indoor air quality research until now has concentrated mainly on negative impacts on occupants. The aim has been to reduce the pollution in the indoor air by using low emitting materials, proper maintenance of ventilation systems, efficient ventilation, etc. The pleasant effect on occupants of enrichments of the indoor air with positive stimulating olfactory substances is discussed at this congress by von Kempski (1997). Requirements for the selection of correct olfactory substances and their concentration into the supply air, as well as design recommendations, are outlined by the author.

Lighting versus thermal comfort and energy savings

Good lighting enables occupants to see easily and to perform their work efficiently without strain or fatigue. Good lighting also enhances the appearance of a space and provides a pleasant working environment. Lighting should be energy-efficient because in many buildings it is a substantial part of the energy consumption. In offices, for example, the lighting often accounts for around 50% of the electricity used, and lighting costs can exceed those for heating. Energy savings may be achieved by reductions in lighting power density. A decrease in lighting power density will reduce the heat produced by lighting and this will reduce the energy need for cooling, particularly in warm climates. However, before any steps are taken, it is important to know how the reduction in lighting power density will be accepted by the occupants and how it will affect their performance, what the design of the lighting will be, how much energy will be saved, etc. These aspects have been investigated in a comprehensive study by Newsham and Veitch (1997) and presented at this forum. Both computer simulations and human subject experiments have been performed, comprising different buildings and combinations of environmental conditions. Potential for substantial energy savings has been identified by reduction of lighting power below the limits of present practice, without a significant impact on occupants' comfort and preferences.

The lighting provided through windows is important for energy savings, quality of the light, psychological and physiological impacts on occupants, etc. Window design has been studied by Aghemo and Pellegrino (1997). Five window configurations have been compared as regards their daylight factor, uniformity ratio of illuminance, and daylight glare index. The performance of the five window options is compared, based on physical measurements. A further subjective investigation will provide final recommendations needed in practice.

Combined effects of different types of indoor environment

In daily life, occupants are exposed simultaneously to all components of the indoor environment, i.e. thermal, acoustic, visual and olfactory. It is therefore important to know the impact of their combined effects on the occupants. Studies on combined effects of thermal, acoustic and olfactory components of the indoor environment have already been reported in the literature (e.g. Clausen et al. 1994). In laboratory experiments human subjects have assessed and compared their sensation under different levels of air temperature, air quality and noise. Experiments with combinations of the three environmental parameters have been performed as well. The planning of the experiment and the analyses of the results has been performed to provide average data for the pool of tested subject, e.g. the traditional method used to study human response to thermal, olfactory and acoustic environment separately. Results, which are important for understanding human response to combined exposure of the three indoor environment components, are identified. However, a new approach which takes into account the individual differences between people has to be employed in the future to study the combined effect of different type of indoor environment on occupants. There is not a single combination of the four types of indoor environment that can be preferred by all occupants in a room. In many cases in practice occupants have to make a compromise in selection of different levels of thermal, olfactory, visual and acoustic environment. This compromise is very different from occupant to occupant.

In a paper by Achard et al. (1997) the “radiative comfort“ of occupants in office buildings during seasons without heating is evaluated. The expression “radiative comfort” is used by the authors to characterise the thermal and the visual components of occupants’ comfort. Two numerical models, one for visual and the other for the thermal aspect of the environment, are used to identify the frequency and impact of visual and thermal effects. The results show that discomfort due to visual effects can be expected more frequently in practice than discomfort due to thermal effects. The authors conclude that the changes of the visual environment are instantaneous while the changes of the thermal environment have a time-delay depending on the thermal inertia of the rooms. The visual environment is assessed by the glare index while the thermal environment is assessed by the PMV index. The PMV index has been used previously to assess time performance of HVAC systems. When human response is considered, however, one should remember that the PMV-PPD and the other indices included in the present standards are developed on the basis of experimental data from human subject experiments under steady-state conditions and are inappropriate for use in a transient environment. The predictions will be incorrect if the application range of the indices in not considered. Furthermore, one should remember that human response to changes of thermal environment is instant.

PREDICTION OF INDOOR CLIMATE

Requirements for an acceptable thermal environment are specified in the standards (ISO 7730 1994, EN ISO Standard 27730 1995, ASHRAE Standards 55 1992, etc.). For winter and summer conditions standards recommend the operative temperature in rooms for people wearing typical seasonal clothing with an average thermal insulation, performing light, mainly sedentary work, i.e. for environments in offices, schools, etc. Certain humidity ranges are defined as well. The operative temperature is defined as the uniform temperature of an imaginary black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual non-uniform environment. The standards also specify limits for local discomfort due to radiant temperature asymmetry, vertical temperature difference, cold or warm floors and draught. Several computer models have been used over the last 10-15 years to predict occupants' thermal comfort. ISO Standard 7730 (1994) and EN ISO Standard 27730 (1995) include appendices with a computer program for calculating PMV-PPD indices. ASHRAE has sponsored the development of a thermal comfort prediction tool which can be used by HVAC engineers and architects during building design (Fountain and Huizenga 1996). The tool is limited to prediction of the thermal environment. A much more advanced hypertextual tool for comfort design is developed and presented at this meeting by Filippi et al. (1997). The hypertextual tool allows a complete prediction of the indoor climate to be made, including thermal, olfactory, visual and acoustic comfort, according to the present standards and pre-standards as well as recent knowledge in the field of indoor climate. Based on both informative text and routines for the calculation of comfort indices, the tool enables different categories of environmental quality to be designed, taking into account the type of building and space, reference season, etc. The thermal, acoustic, olfactory and visual environment in spaces can be described in detail by iso-comfort curves. At present the tool is limited to determination of comfort indices from known environmental conditions. However, its further development includes identification of indoor environmental conditions correlated to adopted technical solutions and to outdoor conditions.

ASSESSMENT OF INDOOR THERMAL ENVIRONMENT

Are the design criteria used always correct?

It is common practice to assess the performance of a newly built HVAC system prior to its use. An important aim of the assessment is to identify and make sure that the system provides an acceptable thermal environment for the future occupants. For this purpose, both theoretical calculations and physical measurements are performed. Most often the physical measurements are performed in full-scale rooms. The measured physical quantities and the location of the measurements are specified in the present standards (ISO Standard 7726 1985, ASHRAE Standard 55 1992, ASHRAE Standard 113 1990).

The data from the measurements are used to assess whether the thermal environment in a space complies with the requirements for general thermal comfort as well as to assess local thermal discomfort. However, very often the assessment of the thermal environment is not performed as required in the standards. In some cases the assessment is limited only to identification of general thermal comfort conditions, while the assessment of local thermal discomfort is ignored or is based on inappropriate criteria. In other cases the assessment is based on measurements at inadequate locations and heights within spaces.

Several studies on the assessment of HVAC systems are presented at this forum. Magyar and Nyitrai (1997) report results from an investigation on wall and ceiling heating and cooling systems. A computer program that allows for the calculation of temperature distribution on the surface of the walls and the PMV distribution within the entire space has been developed and validated by measurements using several combinations of number and location of heated surfaces. According to the validation made by the authors, the accuracy of the predictions is within an acceptable level. A risk of local thermal discomfort due to radiant temperature asymmetry exists with the proposed system. However, this is not addressed in the paper. Further, it is important to compare the system with other heating and cooling systems and to outline its advantages and disadvantages.

The impact of natural ventilation through windows on occupants' thermal comfort is reported by Zeidler and Fitzner (1997). Calculations of airflow volume through a window, cooling power of the natural ventilation, velocity, temperature, etc. are performed. The findings of this study are firstly, that the maximum specific cooling power of natural ventilation is 35 W/m^2, and secondly, that by natural ventilation, thermal comfort in spaces cannot be guaranteed when the outdoor temperature is below 10°C. The authors conclude that ventilation by opening windows has a limited application. In this study, the assessment of the thermal environment is limited to local discomfort due to draught and vertical temperature difference, which is justified because the investigation is performed in the zone of comfortable room air temperatures providing conditions of acceptable general thermal comfort. The assessment of draught is based on the mean velocity limitation of 0.15 m/s. However, this does not comply with the recommendations in the standards. The measuring locations are not identified. The velocity measurements are taken at 0.1 m above the floor. It is not considered that the height above the floor where the maximum velocity appears in the flow may change with the distance from the window. Thus the draught assessment made may not be accurate. Air temperature measurements at several locations and single velocity measurements as performed by Roussau (1997) in naturally ventilated rooms may not be enough for thermal comfort assessment as well.

The PPD index (EN ISO 27730 1995) and the ADPI index (ASHRAE Standard 113 1990) are used by Meslem et al. (1997) to assess the thermal environment in a room with mixing ventilation. Database from comprehensive measurements of air velocity and temperature field in a full-scale test room with a cold air diffusion supply under numerous combinations of supply airflow rate, supply and room air temperature difference, is used to establish relationships that may be used to predict the airflow distribution in a room. The thermal environment is assessed as well. However, the assessment is not performed according to the requirements in the standards. Vertical temperature differences greater than the 3°C limit as prescribed in the ISO Standard 7730 (1994), EN ISO Standard 27730 (1995) and ASHRAE Standard 55 (1992) may occur in the occupied zone of a space under the tested experimental conditions. This, however is not reported in the paper. The three standards recommend predicting draught risk in the occupied zone based on point measurements of air temperature, mean velocity and turbulence intensity. In this study however, draught discomfort is identified by the ADPI index recommended by ASHRAE Standard 113 (1990). The problem with the ADPI index is that it has rather limited application in practice and does not provide correct draught assessment.

What is wrong with the ADPI index?

The ADPI index, included in ASHRAE's literature (ASHRAE Handbook of Fundamentals 1993, ASHRAE standard 113 1990) is used to assess how "draughty" the environment is. The ADPI index requires air velocity and temperature measurements on a minimum of two planes in the room. On each plane, measurements are performed at a minimum of five locations and at four heights, 0.1, 0.6, 1.1 and 1.7 m above the floor. At each test point, the effective draft temperature, θ, is calculated as:

$$\theta = t_x - t_c - 8 \cdot (v_x - 0.15) \qquad (1)$$

In the above equation t_x (°C) is time-averaged air temperature at the test point, t_c (°C) is the average test zone temperature and v_x (m/s) is the mean velocity at the test point. The ADPI index is calculated as the percentage of test points where the effective draught temperature and velocity meet the criteria: $-1.7°C<\theta<1.1°C$ and v_x <0.35 m/s. Typically ADPI above 80% is acceptable.

The ADPI index was originally developed for use in rooms with mixing ventilation where the airflow in the occupied zone is expected to be uniform. Therefore it has a limited application in rooms with other principles of ventilation that provide non-uniform, but still acceptable airflow distribution, such as displacement ventilation, under-floor ventilation, etc. Furthermore, the methodology of the ADPI index is based on considerations for uniform air distribution but is used for assessment of occupants' draught discomfort. Therefore, it leads to incorrect assessments as demonstrated by the following examples.

Let us assume that measurements are performed at 10 locations in a room with four air supply devices located at the ceiling. At each location, measurements are performed at four heights, 0.1, 0.6, 1.1 and 1.7 m above the floor. This gives totally 40 measurements. The ADPI will be 80% if in eight of the 40 measuring points the velocity is higher than 0.35 m/s. Due, for example, to poor design of ceiling air supply devices, the eight measuring points with a velocity higher than 0.35 m/s can be grouped at two locations (four measurement points at each location) or can be spread at eight out of the 10 measurement locations (one measurement point at each location). In both scenarios, the ADPI will identify the environment as equally acceptable, ADPI=80%. However, this assessment will be wrong. Occupants in a room will complain of high velocities regardless of whether they are felt at one body part, for example the head, corresponding to the measuring point at the height 1.1 m above the floor, or at four body parts corresponding to the four measurement heights (0.1, 0.6, 1.1 and 1.7 m). Thus in the first scenario, it may be expected that only at two of the location occupants will experience draught while in the second scenario, eight out of ten locations in the room will be unacceptable for the occupants due to the high velocities. Another example is a room with displacement ventilation where high air velocities occur mainly near the floor. At ten measurement locations and four measurement points at each location (totally 40 measurement points), an ADPI of 80% will classify the room as acceptable even if velocities higher than 0.35 m/s are measured at eight out of the ten locations. This again will be a wrong assessment as in reality, eight out of ten occupants seated at the measurement locations will probably experience draught at the feet.

Why is there a need of field studies?

Field assessment of the indoor environment based on occupant response is a method of investigation often used. The field studies may have different purposes. Some field studies are performed to identify causes of occupant complaints in an existing indoor environment and to introduce improvements that will make the environment acceptable. An example of such an approach is reported at this forum by Verbeeck and Hens (1997). Their study started with a questionnaire survey of 1785 employees in 6 buildings. Then long-term temperature measurements (wall surface, floor, ceiling, air temperature at different heights) and short-term measurements (air velocity, standard deviation of velocity, radiant temperature and relative humidity) were performed, during both the summer and winter period. The measurements were followed by computer simulations of the indoor thermal climate. As a result, suggestions for modifications of the HVAC systems were proposed and evaluated. Discussions with the authors of the study will definitely reveal many details of the study and will improve the realisation of other similar future studies.

Several field studies have also been performed to verify the requirements in the standards. ASHRAE has sponsored four large field studies in different climates: in a temperate climate (Schiller et al. 1988), in a hot-humid climate (de Dear et al. 1994), in a cold climate (Donnini et al. 1996) and in a hot-dry climate (this study is in progress). The field studies are also performed to validate existing models in the literature or new models. For example, a field survey in seven multi-storey office buildings in Indonesia has been performed by Karyono (1977) to validate both adaptive models developed by Humphreys (1981) and de Dear and Auliciems (1985) and the requirements in the ISO standard 7730 (1994). The adaptive models known from the literature correlate the indoor temperature preferred by occupants with the outdoor temperature. Karyono has collected a subjective response of 596 office workers. The neutral temperature preferred by the occupants has been identified and compared with the neutral temperature predicted according to the ISO Standard 7730 (1994) and the adaptive models developed by Humphreys (1981) and de Dear and Auliciems (1985). The conclusion of this study is that the difference in the actual comfortable temperature identified from subjects' votes and the predicted neutral temperature according to ISO Standard 7730 and the adaptive models is insignificant. A comparison of these results with results from previous field studies is recommended as a next step in this research.

Why are there discrepancies in field and laboratory studies?

During the last few years discrepancies between field studies and the requirements in the standards based on laboratory experiments have been reported (Schiller et al. 1988, de Dear et al. 1994, Donnini et al. 1996) as well as discrepancies between subjective response collected in the field and predicted response based on field measurements. Several factors, such as differences in questionnaires used, accuracy of the measurements, analyses of the results, etc., could have caused the inconsistencies. The importance of the method for analysing the results is discussed in this congress by Conte and Fato (1997). A new method, the fuzzy set theory, and the classical method of statistical analyses are used to analyse and compare results of a database on occupants’ response and predictions based on physical measurements collected in a field study. The comparison shows an improvement in the correlation between the occupants’ response and the predictions when the fuzzy theory is used. Further work on the use of this new approach may be expected in the future.

Most often field measurements are restricted to assessment of only one type of indoor environment components, for example the thermal environment. However, occupants' response might be affected by the air quality in the space, the level of noise or other non-thermal factors. A recent study by Fang et al. (1996) for example, shows that the air quality perceived by occupants in a room will improve when the air temperature is decreased. It may therefore be expected that in spaces with a poor air quality, occupants may require a lower air temperature not to improve their thermal comfort, but rather to improve their olfactory perception. This kind of interaction may become a reason for incorrect conclusions if not considered in the design of the questionnaires or during the analyses of the results.

The importance of the questionnaire design is discussed at this forum by Levermore and Leventis (1997). They have used a questionnaire rating liking and importance of up to 24 environmental, organisational and human factors. The questionnaire has been used in a field survey in 8 office buildings. Response from 600 occupants has been collected and analysed. The results indicate that factors such as colleagues, health, daylight, space and temperature are more important than colour, appearance, attractiveness and privacy.

Accuracy of the measurements, if not considered, may also be a reason for discrepancies between human response and predictions based on measurements, as observed in some studies. Melikov and Sawachi (1992), for example reported a difference of up to 100% in mean velocity and turbulence intensity measured under identical conditions by five low velocity thermal anemometers, all available on the market.

WHO IS RESPONSIBLE FOR A COMFORTABLE INDOOR ENVIRONMENT?

The HVAC engineers are able today to design good indoor climate for the occupants based on knowledge from the indoor climate research as well as on new concepts and developments in HVAC technology and control. However, even if well designed, the HVAC system may cause serious complaints from the occupants if it is improperly operated and maintained.

The building managers and operators of HVAC systems have the important task to maintain an acceptable indoor environment in buildings. HVAC system which is not properly maintained and operated may cause serious disturbances for the occupants. In case of high velocities for example, occupants may stop the ventilation system, plug air-supply terminals or they may open windows, if it is too warm in the room, which will normally aggravate the indoor climate for the rest of the occupants. As a result more complaints from the indoor environment will be reported by the occupants and their productivity may decrease. In many cases the energy consumption may increase. This is frustrating for the HVAC engineer and a threat to the image of the heating, ventilation and air-conditioning industry as a whole. The problems associated with a lack of commissioning, which ensures proper operation of the HVAC system, are being expressed in the form of unreliable system operation, indoor climate problems and higher operation and maintenance costs.

The building occupant has a significant role in maintaining of good indoor climate and efficient use of energy in buildings. The greater the understanding of the variables affecting indoor climate and the opportunities for maintaining an acceptable indoor climate, the greater the chance for general satisfaction with the environment. During field studies, several cases of incorrect operation of HVAC systems have been identified, with resulting unsatisfactory indoor climate conditions, mainly due to lack of knowledge, passivity and in some cases improper actions of the occupants. For example, in rooms with displacement ventilation, occupants often block air terminal devices with furniture and office machines and this changes the air distribution in rooms as well as the working conditions of the HVAC system as a whole. Similar problems have been identified in rooms with under-floor HVAC systems. It should be also remembered that each occupant can achieve a greater degree of satisfaction with the thermal environment by modifying and adapting his clothing appropriately. Simple means, such as local cooling by small desk fans or local heating, are efficient but not always used by the occupants as ways to diminish individual differences and to improve thermal comfort. The occupants must play an active part in the use and maintenance of the HVAC system.

Architects have to play an important role in the design process of acceptable indoor environment. Windows, for example, are an important architectural element in building design, and they have a direct impact on both the visual and the thermal environment in spaces. Strong down-draughts due to large and improperly designed and located windows may cause significant draught complaints from occupants during the winter.

All parties, design engineers, managers, architects and users of HVAC systems, are responsible for achieving an acceptable indoor climate in buildings at low energy costs. Education programs will help in this process by disseminating knowledge to designers, operators and users.

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