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ARE THE THERMAL FACTORS CRITICAL FOR HUMANS ADEQUATELY CONSIDERED IN THE DESIGN OF NEW HEATING AND AIR-CONDITIONING SYSTEMS?

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Abstract

The major aim of a building is to provide a healthy and comfortable environment for the occupants. For this purpose it is preferable if the influence of the building and installations on human comfort can be predicted already at the design stage. This paper discusses the problems in predicting the thermal environment. The requirements for a comfortable thermal environment based on existing standards are presented, followed by a discussion on different methods for predicting the relation between design of building, heating and air-conditioning systems, and the thermal environment. This indicates that while surface-, radiant- and air temperatures may be predicted in the design stage, it is often not possible to predict air velocities and vertical air temperature gradients. Finally, the question of which factors are important in the design and development of new heating and air-conditioning system are discussed.

Introduction

The main purpose of most heating and air-conditioning systems is to provide an acceptable thermal environment for human beings. Based on many years of research, international standards have been established, which quantitatively specify requirements for acceptable thermal environments. (1), (12), (17). The best and most efficient way is to consider those requirements as early as possible in a building or developing process. At the design stage, it is, then, desirable to predict the indoor thermal climate, that will result from a given combination of building construction, heating and/or air-conditioning system, and outdoor climate.

In existing building codes or standards for sizing the heating- and air-conditioning systems very few requirements have been listed for the indoor thermal environment. Mostly, it is only required that at a given outdoor design temperature the heating- and/or air-conditioning system should be able to keep the indoor temperature above (heating period, winter) or below (cooling period, summer) a certain value. Until recently the indoor temperature in existing codes has been regarded as air temperature. In new standards and codes, however, it is discussed to introduce the operative temperature. Several large computer programs (10), (11) exist that can be used to predict heating and cooling loads, indoor air temperatures, surface temperature and humidity, both in steady-state and non-steady state conditions. These programs are, however, often difficult and expensive and are mainly used to calculate energy consumption for large buildings.

If in the future the architect and engineer are to take into account all the requirements for an acceptable thermal environment, it is necessary that the appropriate tool in the form of predictive calculation procedures are available. In the 70's and beginning of the 80's the computer programs dealing with buildings and heating and air-conditioning systems mainly focused on the prediction of energy costs. This is still an important factor; but the requirements for an acceptable environment must in the future, get a much higher priority.

The cost of energy for heating and cooling of an office is in modern buildings less than 1% of the costs for salary and office facilities. This means that if the heating and air-conditioning system is designed to minimize energy costs at the cost of the thermal comfort of the occupants, the savings will readily be lost by a decrease in the performance of the occupants (more sick-leave, dispute about conditions, etc.).

The following sections consider, in turn: the critical factors and requirements for an acceptable thermal environment; factors that can be taken into account at the design stage; and finally the most important factors for design, and development of new systems.

Requirements for an Acceptable Thermal Environment

The following requirements are included in an international standard, ISO 7730 (12) and similar requirements may be found in ASHRAE standard 55–81 (1) and NKB guidelines (17). A first requirement for an acceptable thermal environment is that a person feels thermally neutral for the body as a whole i.e. he does not know whether he would prefer a higher or lower ambient temperature level. This is evaluated by the PMV–PPD index (Fig. 1) which is influenced by the following factors:

Personal factors:

Activity level	M (met, W/m^2)
Thermal insulation of clothing	I_{cl} (clo, $m^2C°/w$

Environmental parameters:

Air temperature	t_a (°C)
Mean radiant temperature	$\bar{t}_r$ (°C)
Air velocity	v_a (m/s)
Air humidity (water vapour pressure)	p_a (Pa)

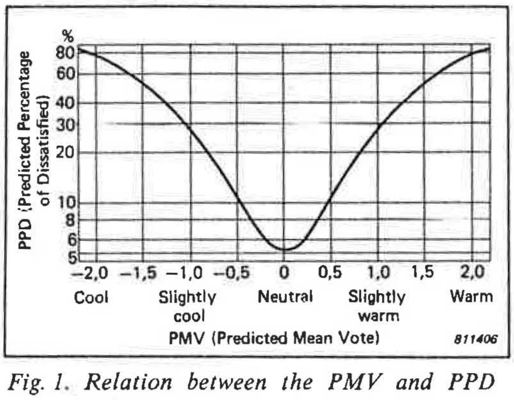

Fig. 1. Relation between the PMV and PPD indices

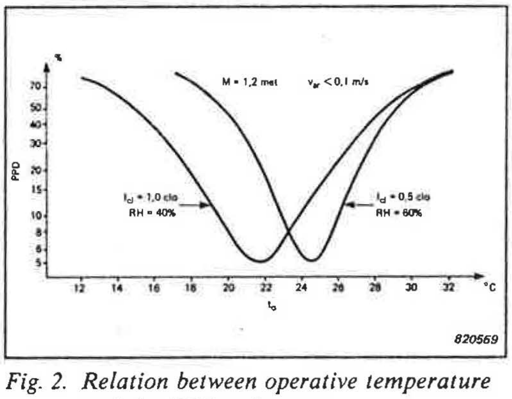

Fig. 2. Relation between operative temperature and the PPD value

A PMV value = 0 is equivalent to thermal neutrality. In ISO 7730 the recommended limits for an acceptable thermal environment are:

$$-0{,}5 < \text{PMV} < 0{,}5$$
$$\text{PPD} < 10\%$$

The use of recommended limits aro illustrated in Fig. 2 for a typical winter situation (heating period, clothing insulation 1,0 clo) where the occupants have light, mainly sedentary work, 1,2 met (office, school) the recommended operative temperature range is 20–24°C. In summer (clothing insulation 0,5 clo) the corresponding interval is 23–26°C.

Thermal neutrality as predicted by the comfort equation or described by the PMV–PPD indices is not the only condition for thermal comfort. A person may feel thermally neutral for the body as a whole, but may not be comfortable if one part of the body is warm and another cold. It is therefore a further requirement for thermal comfort that no local warm or cold discomfort exists at any part of the human body. Such local discomfort may be caused by an asymmetric radiant field, by a local convective cooling (draught), by contact with a warm or a cold floor, or by a vertical air temperature gradient.

In ISO 7730 the recommended limits for avoiding local discomfort for people occupied with light, mainly sedentary work (1,2 met) are as follows:

The radiant temperature asymmetry (Δt_{pr}) from windows or other cold vertical surfaces shall be less than 10°C (in relation to a small vertical plane 0,6 m above the floor).

The radiant temperature asymmetry (Δt_{pr}) from a heated ceiling must be less than 5°C (in relation to a small horizontal plane 0,6 m above the floor).

Mean air velocity (3 min) v_a shall be less than 0,15 m/s during winter (heating period), i.e. operative temperature between 20 and 24°C.

Mean air velocity (3 min), v_a, less than 0,25 m/s during summer (cooling period), i.e. operative temperatures between 23 and 26°C.

Vertical air temperature difference between 1,1 and 0,1 m above floor (head and ankle level) shall be less than 3°C.

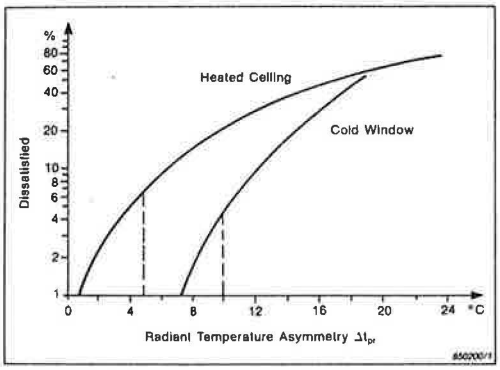

Fig. 3. Relation between the radiant temperature asymmetry and the expected number of dissatisfied

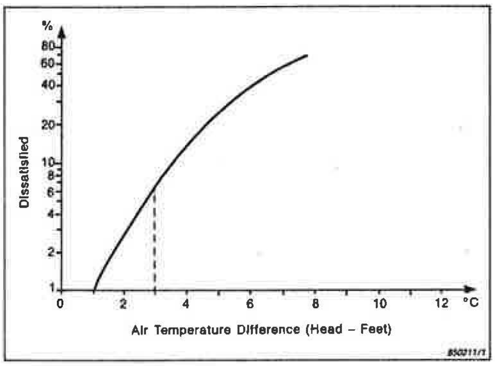

Fig. 4. Relation between the vertical air temperature difference and the expected number of dissatisfied

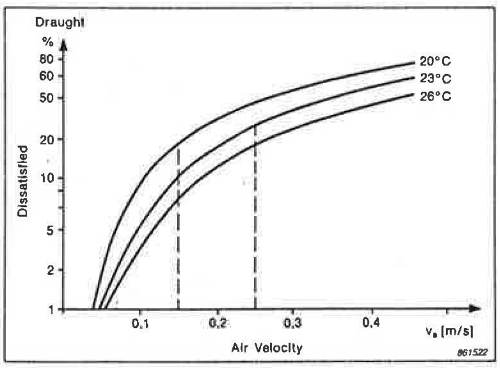

Fig. 5. Relation between the air velocity (medium turbulence) and the expected percentage feeling draught

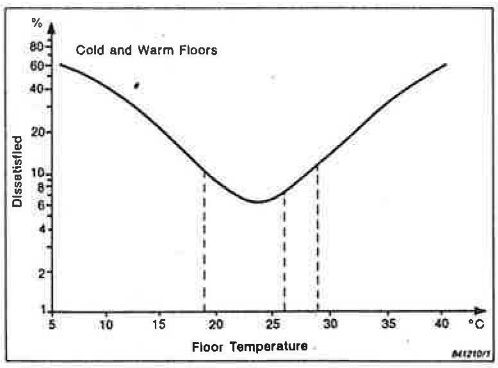

Fig. 6. Relation between the floor temperature and the expected percentage of dissatisfied (people with shoes)

Surface temperature of the floor shall normally be between 19 and 26°C, but floor heating systems can be designed for 29°C.

In ASHRAE 55–81 there has also been specified the following limits for temperature ramps and cycling temperatures:

by temperature ramps a rate of change of 0,5°C/h is recommended
by cycling temperatures the rate of change shall be less than 3,5°C/h with a peak to peak amplitude less than 3,5°C.

The above requirements are based on several research results ((2–9), (14), (18–20), (22)). In several studies the relation between the percentage of dissatisfied and the different local thermal discomfort parameter has been established. This relation is shown in Fig. 3 for radiant temperature asymmetry, in Fig. 4 for vertical air temperature differences and in Fig. 5 for floor temperatures. The requirements for air velocity is in existing standards based on a mean air velocity and an air temperature range (see Fig. 6). New research results (8) have however, shown that fluctuation of air velocity also have an influence of the number of people sensing draught. This is illustrated in Fig. 7. The number of people feeling draught may be estimated from the equation:

$$\text{Percentage dissatisfied} = (34 - t_a)\,(v_a - 0{,}05)^{0{,}6223}\,(3{,}143 + 0{,}3696 \cdot \text{SD}) \qquad (1)$$

where v_a = mean air velocity (3 min) m/s
SD = standard deviation of air velocity (3 min) m/s
t_a = air temperature, °C

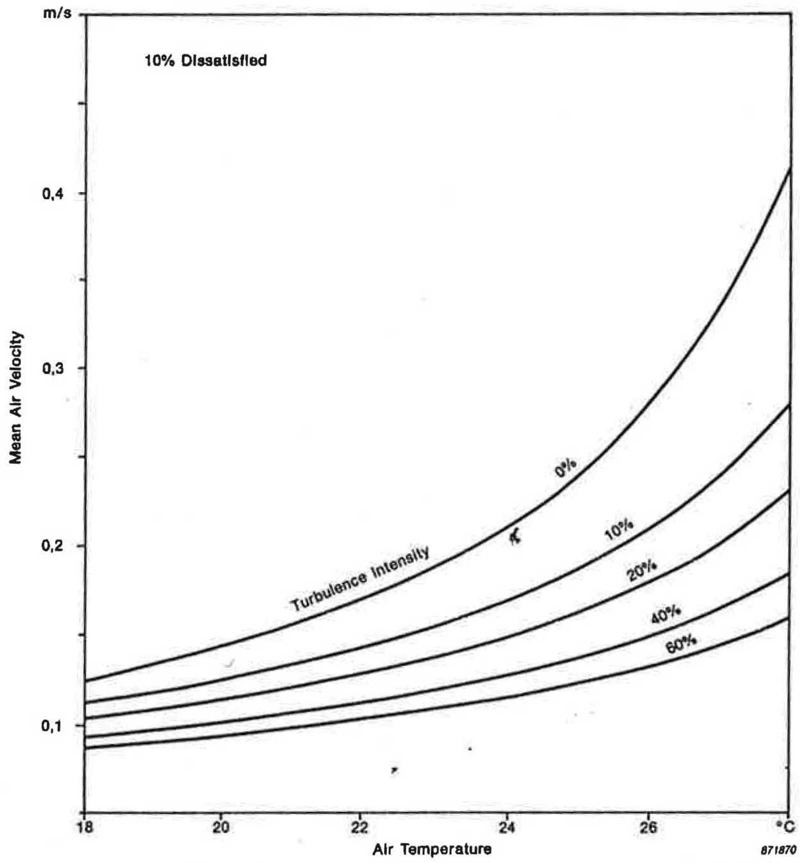

Fig. 7. Combinations of mean air velocity, air temperature and turbulence intensity, which cause 10% dissatisfied. Calculated from the model of draught risk, Fanger et. al.

Methods for Predicting the Thermal Parameters

To be able to meet the requirement outlined in the previous section it is important already at the design stage to try to predict the parameters critical for human comfort.

The PMV–PPD Index can be calculated from the six parameters (activity, clothing, air temperature, mean rad. temperature, air velocity, humidity). The two personal factors, activity and clothing are fixed by taking into account the use of the room/building and the time of year.

Air temperature and surface temperature may be estimated by setting up a heat balance equation for the room/building. This heat balance consists of a heat balance for each of the surfaces (walls, floor, ceiling, windows, heated surfaces) by taking into account internal heat exchange by radiation to other surfaces, convection to the air, conduction through the construction, and external heat exchange to the outside or neighbouring rooms. A heat balance for the air is established by taking into account convective heat exchange to all surrounding surfaces heat exchange by infiltration air, and ventilation and heat input from internal sources (people, machines etc.). This is the basis of equations which are being used in existing computer programs.

The humidity (vapour pressure or relative humidity) may be calculated from similar equations based on air infiltration, ventilation and internal sources (people, cooking etc.).

Mean radiant temperature is then calculated from the calculated surface temperatures and the corresponding angle factors for a person (5, 13, 17, 21).

Air Velocity is not calculated in the above mentioned computer programs. Normally it is assumed to be less than 0,1 m/s. There exists however, some large models for prediction of the air velocity distribution in ventilated spaces (15, 16). These programs are very difficult and expensive to run and are not usable in a normal design procedure.

The calculation mentioned above may be done for both steady-state and non-steady-state conditions by taking into account the heat capacity of a building. In the latter case it is then also possible to calculate temperature ramps or cycling temperatures due to change in outside conditions or changes in internal loads.

Radiant temperature asymmetry is calculated in the same way as mean radiant temperature by use of the surface temperatures and angle factors to a small plane element (1, 13, 17, 21).

Floor temperature is calculated from the heat balance equation of the floor (heat exchange to internal air and surfaces, heat conduction through the floor construction, heat exchange with the ground, cellar or lower rooms). For a floor heating system the design heat loss per m^2 of heated floor surface has to be taken into account.

Air velocities (draught) are as mentioned earlier very difficult to predict at the design stage. For evaluating the draught-risk it is not only air velocity but also air temperature and air velocity fluctuations (standard deviation) which have to be estimated. Air velocities may be caused by ventilation systems or by thermal convection currents. There exists some methods for predicting the air temperature and air velocity of down draught from cold surfaces like windows and walls (23). The design of outlets and their position are often studied in full scale models; but this is only economically feasible for greater building projects. There is a need for usable methods for prediction of air velocities.

Vertical air temperature differences are also not really possible to predict in the design stage. Most often a uniform temperature distribution is assumed in a room.

The physical parameters like air temperature, surface temperature, mean radiant temperature, plane radiant temperature and humidity may be estimated at the design stage, while today it is not in a usable way possible to predict the air velocity and air temperature distribution in a room.

A simplified calculation method for predicting the indoor thermal climate at the design stage has been presented by Olesen (21).

Development and Design of New Heating and Air-Conditiong Systems

One may ask if the requirements for an acceptable thermal environment can be fulfilled by a proper design of a building and use of existing heating- and air-conditioning systems? Yes, they can; but there is not one system which is the best. This depends from case to case on the building design and the use of the building.

From the requirements it is seen that the design shall try to provide conditions as uniform as possible i.e. no radiant asymmetry, low air velocities, uniform temperature distribution. This is not only done by the design of the heating and air-conditioning system; but what may be more important the design of the building. In many cases a heating- or air-conditioning system may compensate for thermal problems caused by the design of the building.

Radiant asymmetry is mainly caused by large windows (cold in winter, direct sunshine in summer). This may be avoided by the use of multi-pane windows (double or triple), high insulative windows (gas filled) and in some extreme cases by heated windows. This will at the same time reduce the risk for too high air velocities due to down draught along the colder window surface. Also a proper position of the heater (panel heater) may compensate for the cold radiation from a window.

The risk of too high vertical temperature differences is normally greater in poorly insulated houses and in rooms heated mainly by convection. In this case low temperature radiant heating systems will normally result in a very uniform temperature distribution.

Low temperature heating systems are beneficial in many ways. First of all due to the uniform conditions which are normally obtained. But there are also advantages in relation to the energy consumption. Lower supply temperatures will result in better efficiency of the boiler and less heat loss in the supply coils (i.e. district heating).

The most difficult task is probably to design ventilation systems with low, uniform air velocities. One development in this direction is the use of displacement ventilation. The risk here is, however, that there will be too low air temperatures along the floor.

To verify the advantage of new designs may, as indicated above, not always be possible by use of calculation methods at the design stage. The only way is then to perform the verification by measurement of the thermal parameters. This is also possible with existing measuring equipment which fulfil the requirements in ISO 7726.

Conclusion

Today we know very well the requirements for an acceptable thermal environment. For the design of buildings and heating and air-conditioning systems it is possible at the design stage to predict the thermal parameters. There is, however, a need for better methods to predict the air temperatures and air velocity in a room. It should also be possible by a proper design to fulfil the requirements for an acceptable thermal environment using existing heating and air-conditioning systems.

In the future these requirements should be included in building codes or codes for the design of heating- and air-conditioning systems. Also it should be specified in any building contract, which requirements for the thermal environment are the basis for the design. Then it is much easier in any later dispute to verify if the requirements have been fulfilled.

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