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Standards for Measuring & Evaluating of the Indoor Thermal Environment

by

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ABSTRACT

The main purpose of most buildings and HVAC systems is to provide a healthy and comfortable indoor climate for the occupant. A very important factor is the thermal environment. In a majority of reported cases of buildings, which had an indoor air quality problem, the thermal environment contributed significantly to the number of occupants being dissatisfied. For the design, evaluation and measurement of the thermal environment national (ASHRAE) and international (ISO) standards, which quantitatively specify requirements for an acceptable environment, have been established. A couple of these standards have recently been revised and more strict requirements related to peoples sensation of draft, have been included.

The present paper will describe the existing guidelines for obtaining an acceptable thermal environment. One requirement is to obtain an acceptable temperature level for a given combination of clothing and activity. Another requirement is to avoid any local thermal discomfort due to radiant temperature asymmetry, draft, vertical air temperature differences and floor temperatures. Regarding draft it is not only a question of a limited air velocity; but also the air temperature and the turbulence of the air flow, will influence peoples sensation of draft.

INTRODUCTION

The knowledge today on how the thermal environment influences people and which requirements are needed to provide an acceptable thermal environment are very extensive. Most people believe that the quality of the thermal environment can be evaluated simply by measuring the air temperature (i.e., the dry-bulb temperature). This is far from accurate. The thermal environment is actually a combination of air temperature, mean radiant temperature, air velocity, humidity, and two personal factors - clothing insulation and activity level - that influence a person's perception of warmth and coolness.

Often two or more of these factors are combined in a kind of thermal index. The operative temperature, which is used in ASHRAE 55-89R, is the mean value between air temperature and mean radiant temperature. As in winter, where outside air temperature and air velocity combine to create a "wind chill" temperature, air temperature, mean radiant temperature and air velocity combine to generate the "equivalent temperature" (9, 10). The equivalent temperature is more or less the temperature you feel in a space. Take, for example, a summer situation, where the air velocity is increased by a ceiling fan. The air temperature stays the same, but people feel cooler because of the higher air velocity. This can be quantified as a decrease in the equivalent temperature. In a typical winter situation, people sitting close to a large window feel cooler than people in the interior zone. The air temperature may be the same both places, but people at the window are exposed to a lower mean radiant temperature and then a lower operative temperature, caused by the low window surface temperature. These examples illustrate that the air temperature alone is not sufficient to evaluate the thermal environment.

Based on many years of research national (ASHRAE 55-81) and international standards (ISO7730) have been published. Both these standards have recently been revised (ASHRAE 55-89R) and will soon be published in the revised form. When evaluating a given thermal environment to see whether it fulfils the requirements recommended in the standards, it will be necessary to perform measurements of the thermal parameters. The requirements to measuring instruments and methods are also specified in ASHRAE 55 and in a separate international standard, ISO7726. The present paper describes the method and requirements in the above standards. A discussion will also be made on the differences between the standards from ASHRAE and ISO. Even if they are very similar there are a couple of differences. The requirements in both standards are, however, based on the same criteria to prescribe conditions, which are acceptable to minimum 80% of the occupants.

REQUIREMENTS FOR AN ACCEPTABLE THERMAL ENVIRONMENT

An acceptable thermal environment is defined (ASHRAE-55, ISO7730) as an environment which at least 80% of the occupants would find thermally acceptable. Acceptance of the thermal environment and the perception of comfort and temperature are related to metabolic heat production, its transfer to the environment, and their resulting physiological adjustments and body temperatures. Dissatisfaction may be caused by warm or cool discomfort for the body as a whole (general thermal discomfort, thermal neutrality). The recommended limits (operative temperature, PMV-index) for general thermal discomfort are based on a 10% dissatisfaction criterion. However, thermal dissatisfaction may also be caused by an undesirable heating or cooling of one particular part of the body (local thermal discomfort). The recommended limits for local thermal discomfort are based on a 5-15% dissatisfaction criterion. Because of individually differences, it is impossible to specify a thermal environment that will satisfy everyone. The individuals who feel general thermal discomfort also may feel local thermal discomfort. Therefore, the percentage of dissatisfied are not additive. It is assumed that totally less than 20% will be dissatisfied when the recommendations in the standards (ASHRAE, ISO) are followed.

General Thermal Comfort

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.

Man's thermal sensation is influenced by the following factors:

Personal factors:

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

Environmental parameters:

Air temperature	t_a	(°C)
Mean radiant temperature	t_r	(°C)
Air velocity	v_a	(m/s)
Air humidity (water vapor pressure)	p_a	(Pa)

These factors can be combined in many ways and provide an acceptable thermal environment. ASHRAE 55-89R does not include an analytical method to combine these factors; but the standard provides guide lines taking into account all factors. Both ISO7730 and ASHRAE Handbook of Fundamentals (ASHRAE, 1989), describes method(s) to estimated the combined influence. ISO7730 standardizes a method using the PMV-PPD index (Fanger, 1982). This method is also described in the ASHRAE Handbook. Based on studies with more than 1300 subjects, an equation was established, which predicts the average thermal sensation of a large group of people (PMV value) on a seven point thermal sensation scale: (+3 Hot, +2 Warm, +1 Slightly Warm, 0 Neutral, -1 Slightly Cool, -2 Cool, -3 Cold).

The quality of the thermal environment may also be expressed as the predicted percentage of dissatisfied, PPD index, which is related to the PMV value (fig. 1). A PMV value = 0 is equivalent to thermal neutrality. In ISO7730 the recommended limits for an acceptable thermal environment are:

$$-0.5 < PMV < 0.5$$
$$PPD < 10\%$$

Figure 1

The use of recommended limits are illustrated in Figure. 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.

Figure 2

The same requirements for the winter situation (heating period) and summer situation (cooling period) are specified in ASHRAE 55-89R for a relative humidity level of 50%. It is important to notice that the specifications are given as operative temperature, which is a mean value between the air- and mean radiant temperature.

ASHRAE specifies a humidity range between a lower limit of 2°C dew point and an upper limit of 60% relative humidity. The humidity only has a minor influence of the recommended comfort zones for winter and summer conditions. In winter the influence on the lower operative temperature limit is from 19.8°C (60% rh) to 20.2°C (2°C dew point, 30% rh). In summer the influence on the upper operative temperature limit is from 25.6°C (60% rh) to 27°C (2°C dew point, 20% rh). As an average an increase in humidity of 10% rh, can be offset by a decrease in temperature of 0.25°C. The humidity limits specified in ASHRAE 55 is not for thermal comfort reasons; but for the impact the relative humidity may have on the indoor air quality.

In ISO7730 there is no limitation for temperature cycling, temperature drifts or ramps, as long as the PMV index is within the recommended range. For temperature cycling ASHRAE 55-89R has no restrictions on the rate of change if peak to peak value of the operative temperature is 1.1°C or less. If the peak to peak value is higher the rate must not exceed 2.2°C/h. The maximum allowable drift or ramp is an operative temperature rate of 0.5°C, which do not exceed the comfort zone guidelines by more than 0.5°C for longer than one hour.

Local Thermal Discomfort

Thermal neutrality as predicted by the comfort equation or described by the PMV-PPD indices or the operative temperature 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 (draft), by contact with a warm or cold floor, or by a vertical air temperature gradient.

In ISO7730 and ASHRAE 55-89R 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).

Vertical air temperature difference between 1.2 and 0.1 m above floor (head and ankle level) shall be less than 3°C. In ASHRAE-55 it is specified as a difference between 0.1m and 1.7m level.

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 a general range of 18-29°C is specified.

One of the most critical factors are draft. Many people are very sensitive to air velocities, so draft is a very common claim in ventilated and air conditioned spaces. The requirements in existing standards are specified as a limit for the mean air velocity of 0.15 m/s in winter conditions, i.e. operative temperature between 20 and 24°C and 0.25 m/s for summer conditions, i.e. operative temperature 23 to 26°C.

New results (Fanger et al., 1988) have, however, shown that fluctuations of air velocity also has a significant influence of peoples sensation of draft. The fluctuations may either be expressed by the standard deviation of the air velocity or by the turbulence intensity Tu, which is equal to standard deviation SDv_a divided by the mean air velocity v_a (SDv_a/v_a). The percentage of people feeling draft (PD) may be estimated from the equation:

$$PD = (34 - t_a)(v_a - 0.05)^{0.6223}(3.143 + 0.3696 \cdot SDv_a)$$

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

In the revised standards, ISO7730 and ASHRAE 55-89R the requirements to draft is based on a 15% dissatisfaction criteria. The recommended limits are shown in figure 3. On hot summer days it may be beneficial to offset the influence of the elevated temperature above 26°C by an increased air velocity above the limits in figure 3. In ISO7730 this relation between increased temperature and increased air velocity can be estimated by using the PMV-equation up to a mean air velocity of 1 m/s. In ASHRAE 55-89R there is a similar method, where a graph shows how much the air velocity should be increased to offset the temperature increase. The maximum allowable air velocity is 0.8 m/s for sedentary occupancy. This will compensate for a temperature increase of 2.5°C i.e. from 26°C to 28.5°C. It is, however, required that the occupant must have individual control of the local air velocity.

Figure 3

MEASUREMENT OF THE THERMAL ENVIRONMENT

To verify that the above criteria are met in a dispute over the indoor climate or by commissioning it is important to be able to measure the parameters. Fortunately, there are instruments available to do that with the necessary accuracy. Some instruments will make an integrated measurements of some of the parameters others will measure the individual parameters. Both ASHRAE 55 and ISO 7726 specifies measuring range, accuracy and response time for instruments.

The recommended measuring heights are also specified. The general rule is to measure at levels which represents head, middle and feet level of person. The PMV-PPD index, operative temperature, radiant temperature asymmetry, humidity and mean air velocity are measured at the middle level i.e. 0.6 m for sedentary and 1.1 m for standing. Draft (air temperature, mean air velocity and standard deviation) and air temperature difference is measured at feet (0.1 m) and head level (1.1 m for sedentary, 1.7 m for standing). The measurement locations must reflects the position of the occupants and common sense must be used, so the instruments are not "shaded" from the exposure of the environment.

One method of finding the PMV-PPD index is to measure each of the four environmental parameters individually, estimate the activity level and clothing insulation from tables and then calculate the PMV-PPD value by means of a computer program or by the use of tables or diagrams. Both computer program and tables are included in ISO7730 or in ASHRAE Handbook of Fundamentals.

A direct measurement can be performed using an integrating instrument (Madsen 1976). The combined influence of air temperature, mean radiant temperature and air velocity is measured by the heated sensor which simulates the dry heat loss from a human being. Based on this measurement and dialed-in values for clothing insulation, activity level and humidity (water vapor pressure) the PMV and PPD indices are estimated. The sensor (fig. 4) is designed to simulate the shape of a human being so that the influence of thermal radiation is measured correctly. When simulating a standing person the transducer is placed in an upright position and when simulating a seated man it is positioned with an inclination of 30° to a vertical axis. The size has also been optimized so that the relation between the convective and radiant heat exchange with the environment is approximately the same as for a human being. Finally, the grey color of the surface simulates much better the radiative properties of human skin/ clothing than the black color which is normally used on a globe thermometer.

Figure 4

Measurement of the Individual Thermal Parameters

ISO7726 includes specifications for the necessary precision when measuring the individual thermal parameters (air temperature, mean radiant temperature, radiant temperature asymmetry, air velocity, humidity). Furthermore, the most common measurement methods are described in annexes. In table 1 the requirements for moderate thermal environments, specified in ISO7726 are shown. Similar requirements are listed in ASHRAE-55.

Table 1

Air temperature (t_a) can be measured in several ways. The main problem is to avoid the influence of the thermal radiation on the sensor. In Table 1 the necessary precisions are listed. It is seen here that these precision values must also be fulfilled if the sensor is exposed to the mean radiant temperature which differs from the air temperature ($[t_r - t_a] < 10°C$). This will then set a limit to the accepted influence of the radiation. To minimize the radiant heat exchange between the sensor and the environment it is recommended to use a very small sensor and to use a radiantly reflective screen around the sensor.

The influence of radiation of a human being is partly described by the mean radiant temperature which is defined in relation to a person, and partly by the radiant temperature asymmetry which is defined in relation to a small plane element.

Mean radiant temperature (t_r) is very difficult to measure with the precision listed in Table 1. One way is to measure all surrounding surface temperatures, estimate the angle factors from the surfaces to a person and then calculate the mean radiant temperature. This is a recommended method in a design state, but in existing buildings and workplaces it is often problematic. The most common way is to use a black globe thermometer. When measuring the globe temperature, air temperature and air velocity it is possible to calculate the mean radiant temperature. The precision is, however, not so good due to an addition of the errors of each measured parameter. Besides, a globe thermometer does not take into account the influence which the thermal radiation from different directions can have on a person.

A better method is to measure the plane radiant temperature in the six main directions (up-down, right-left, front-back) and then estimate the mean radiant temperature as a mean value taking into account the shape factor for person in the different directions.

Radiant temperature asymmetry (Δt_{pr}) is also very difficult to measure. One method is to measure all surrounding surface temperatures, estimate the corresponding angle factors to a small plane element and then calculate the plane radiant temperature (t_{pr}) in the two opposite directions.

A new measuring principle is shown in Fig. 5. Here a black-painted and a gold-painted element are used. Due to the difference in absorptivity the two elements will obtain a temperature difference, which depends on the radiant heat exchange with the surrounding surfaces. In this way it is possible to measure the plane radiant temperature. The sensor is protected from the influence of air velocity by a polyethylene shield, which is transparent to the radiation. The sensor is double-sided and can measure the radiant temperature asymmetry directly.

Figure 5

Air velocity (v_a) is also one of the environmental parameters which can be difficult to measure. As seen from the specifications in Table 1 it is necessary to measure very low air velocities (0.05 m/s) with high precision, low response time and the measurement must not be influenced by the direction of airflow.

These are requirements which can be very difficult to meet and few existing instruments are available for these precise measurements. The most common method is to use a heated anemometer where one part of the sensor is heated to an over temperature compared to the surrounding air. Then the electrical effect necessary to keep this over temperature is a measure of the air velocity. It is, however, important that the sensor has a method for compensating for changes in air temperature and the overheating of the sensor must not be so high that the air movement created by the natural convection from the transducer is of the same magnitude as the air velocity to be measured.

As listed in Table 1, it is a further requirement of instruments for measuring air velocities that a 3 min mean value is given together with the standard deviation.

Humidity can be expressed in many different ways (absolute humidity, water vapor pressure, dew point, wet bulb temperature, relative humidity).

The heat exchange by evaporation from the skin depends on the water vapor pressure (p_a) of the surrounding air. This is normally not obtained by a direct measurement but rather by measuring one of the other parameters for humidity (relative, dew point, wet bulb) and then calculate the water vapor pressure.

Humidity has only a limited influence on the thermal sensation of a person in a moderate thermal environment. Humidity can, however, have a significant influence on parameters like dryness of the respiratory tracts, static electricity, growth of mould, dust mites, etc. In these cases it may often be better to express the humidity as relative humidity or dew point.

CONCLUSION

The knowledge about the thermal environment is much more advanced than the knowledge on indoor air pollutants. The dose-response can often be predicted and the necessary instrumentation is available. Also, it is possible to take most of the factors into account during the design process. But even if there exists well developed standards and guidelines, there is still too many examples of designers, HVAC contractors and building managers not taking the thermal environment serious enough and are not using the standards or guidelines. The thermal environment is an important factor for the quality of the indoor environment and it has such a large impact on the energy consumption in a building. This may often result in that building managers are sacrificing the comfort of people to save energy. This may result in lost productivity, which will cost much more than the savings on energy. But with the established standards it should be possible to create a comfortable environment and at the same time optimize the energy consumption.

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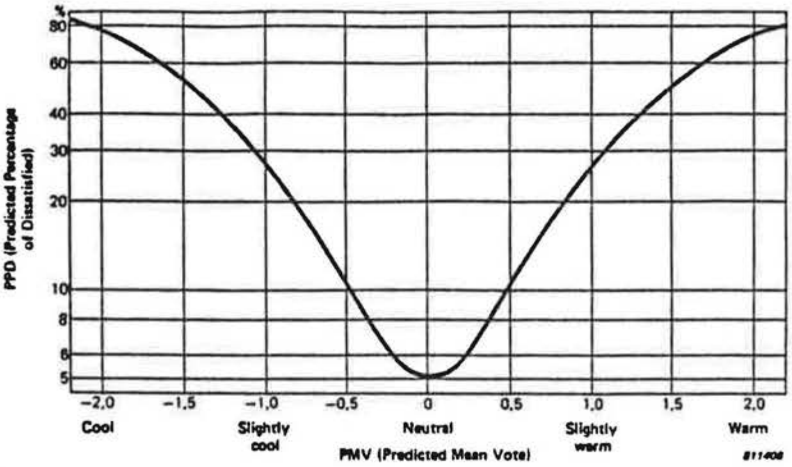


Fig. 1. The relationship between PPD (Predicted Percentage of dissatisfied) and PMV (Predicted Mean Vote)

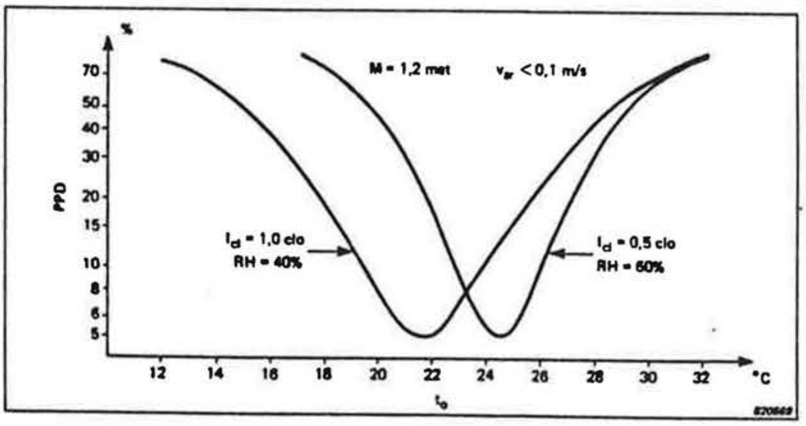


Fig. 2. The relation between operative temperature, t_0, and Predicted Percentage of Dissatisfied (PPD) for winter (clothing I_{cl} = 1,0 clo) and summer (clothing I_{cl} = 0,5 clo) conditions. Activity, M = 1,2 met, Relative Air Velocity, v_{ar} <0,1 m/s and Relative Humidity RH = 40% in winter and RH = 60% in summer

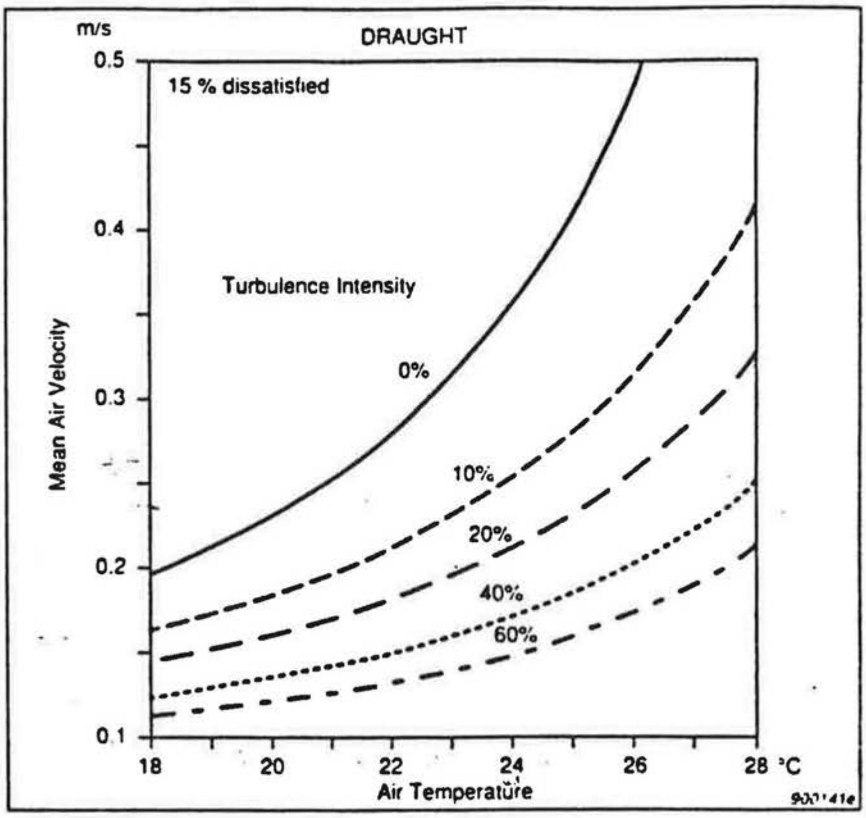


Figure 3: Combination of mean air velocity, air temperature and turbulence intensity which will result in less than 15% dissatisfaction.

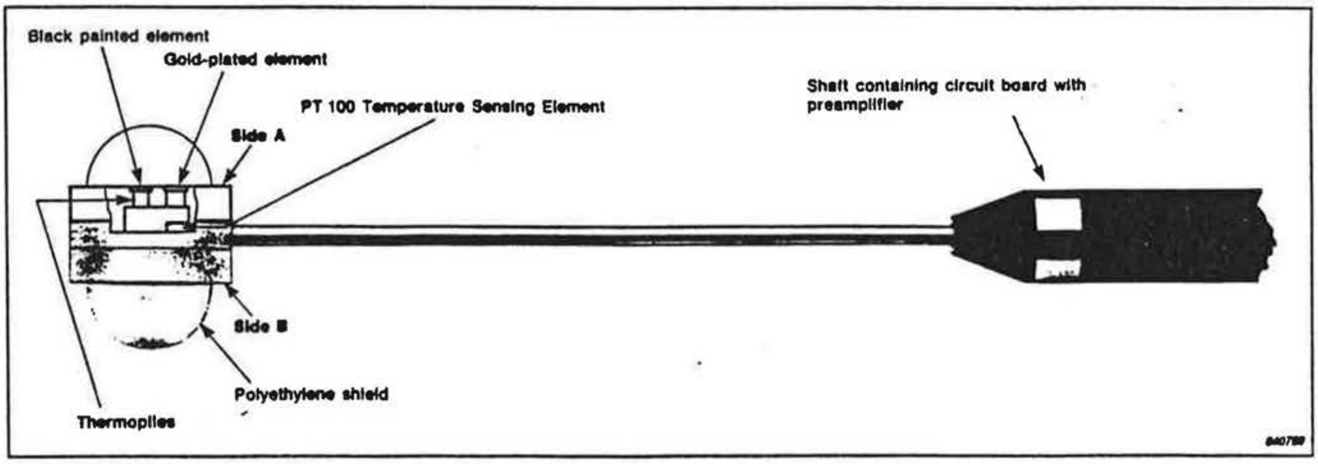
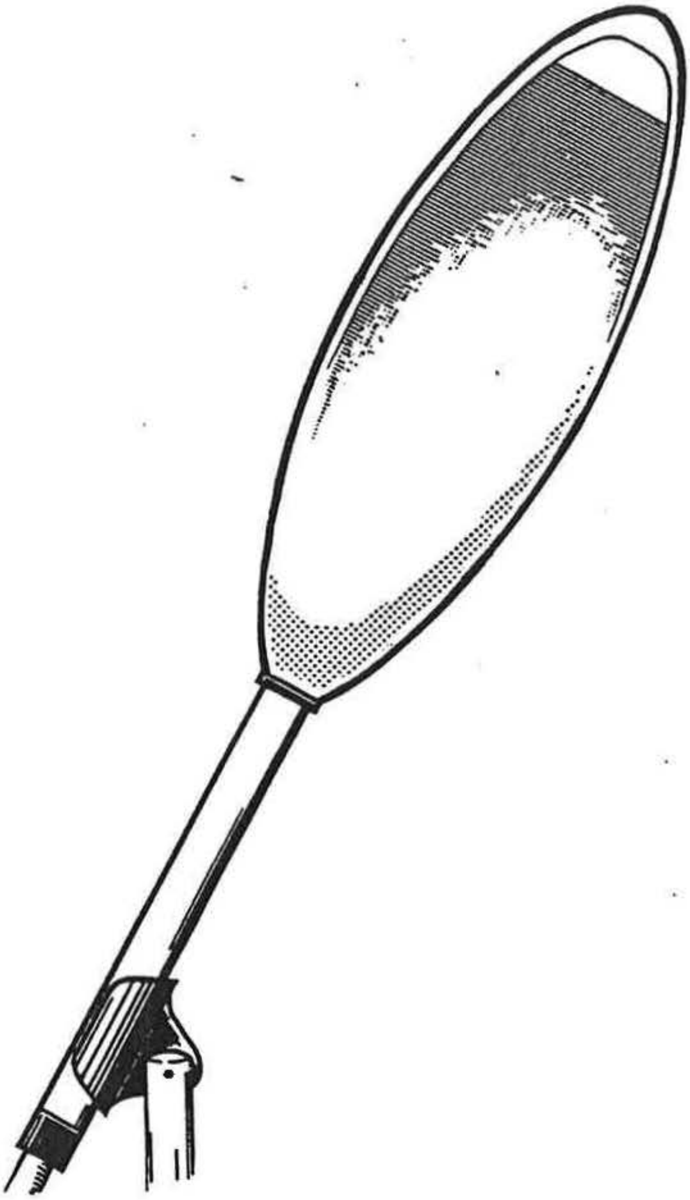


Fig. 4 Radiant Temperature Asymmetry Transducer

Parameter	Unit	Measuring range	Precision		Response time (90%)	Comments
			Specified	Desirable		
Air temperature t_a	°C	10-30	± 0.5	± 0.2	Response time shortest possible	Precision shall be valid for $\lvert t_a - \bar{t}_r \rvert \leq 10^\circ\mathrm{C}$
Surface temperature	°C	0 -50	± 1.0	± 0.5		
Mean radiant temperature $\bar{t}_r$	°C	10-40	± 2.0	± 0.2	Response time shortest possible	This precision may be difficult to obtain by a globe thermometer
Radiant temperature asymmetry Δt_{pr}	°C	0 -20	± 1.0	± 0.5	Response time shortest possible	
Air velocity v_a	m/s	0.05-1.0	$\pm \lvert 0.05 + 0.05\, v_a \rvert$	$\pm \lvert 0.02 + 0.07\, v_a \rvert$	Specified 0.5 s Desirable 0.2 s	Precision shall be fulfilled with a solid angle 3 p sr. Mean value for 3 min. is desirable. Fluctuations are described by the standard deviation.
Humidity p_a	p_a	0.5-2.5	± 150	± 150	Response time shortest possible	Precision shall be valid for $\lvert t_a - \bar{t}_r \rvert \leq 10^\circ\mathrm{C}$

Table [illegible]. Measuring range and precision for measuring individual parameters in a moderate thermal environment. (According to ISO 7726)



EVALUATION AND MEASUREMENT OF THE INDOOR CLIMATE

Indoor air quality is probably the major concern of the building and heating, ventilation, and air conditioning (HVAC) industry in the 90's. Individual corporations have ample cause for concern, too, as billions of dollars are being lost due to decreased productivity, the cost of remodeling buildings and systems, lawsuits, and indoor air quality (IAQ) investigations (1, 2, 3). Building and HVAC system designers try to establish a healthy and comfortable indoor environment for building occupants. Several factors, such as illumination, sound, indoor air quality, and thermal climate, affect the indoor environment and peoples' perceptions of it. This paper, however, will deal only with indoor air quality and the thermal climate, which are most often found to be the causes of an unacceptable environment.

There is no single factor that causes a large number of people to be dissatisfied with their indoor climate. In many cases, a high pollution emission rate from building materials, carpets, and furnishings is responsible. However, several studies have shown that the ventilation system can be a significant problem (3). The HVAC system, generally used to dilute any concentration of gaseous air pollutants or condition the air to obtain an acceptable temperature level, may actually pollute the indoor environment (4). The perceived levels of air pollution will decrease as an increased amount of fresh air is introduced through mechanical ventilation or infiltration. This may result in higher air velocities in the occupied area, or zone, which may increase the chance that some occupants will feel a draft and become dissatisfied.

Investigations have also shown (5) that indoor climate problems are related not only to indoor air pollutants, but to the thermal environment as well. The ventilation system is also a significant factor here. Questions to consider include how much fresh air is being supplied through the duct system and how efficiently the fresh air is distributed into the occupied zone. One must always bear in mind that factors are interrelated, and that when one problem has been identified, its solution may influence other factors.

Guidelines or standards are necessary to help the design engineer, building manager, facility engineer, and contractors. These standards should specify which parameters are important and recommend values for an acceptable indoor climate. These recommendations can then be incorporated into a building contract to specify the desired environment and the conditions (internal and external loads) under which the requirements must be fulfilled.

This may leave safety managers/engineers with several questions. Do we today know enough about the relationship between the different factors and their influences on the occupants? Do we have the tools needed to predict the resulting indoor climate? And do we have the methods and instrumentation needed to measure and evaluate an existing indoor climate? Thanks to extensive research and the development of standards in the 1980s, the answer is yes, especially with regard to questions about the environment. There are now national and international standards for an acceptable thermal environment. There are design tools that can predict the effects of most of the factors at the design stage. Finally, new developments have resulted in commercially available, accurate, and reliable instrumentation. In the area of indoor air quality, however, more work needs to be done, although there have been significant improvements in dose-response knowledge (i.e., response to varying levels/amounts of pollutants), standardization, design tools, and instrumentation.

The following sections will outline recommendations for both indoor air quality and the thermal environment. Each set of recommendations will be followed by a discussion on measuring the relevant factors.

Acceptable Indoor Environment — An Overview

The specifications for an acceptable indoor environment are based primarily on two existing standards from the American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE) (6, 7). In ASHRAE 62-89, "Ventilation for Acceptable Indoor Air Quality," acceptable indoor air quality is defined as: 1) air in which there are no known contaminants in harmful concentrations; and 2) air in which a substantial majority (usually 80%) of the people exposed to it do not express dissatisfaction. In ASHRAE 55-81R, "Thermal Environmental Conditions for Human Occupancy," an acceptable thermal environment is defined

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as an environment which at least 80% of the occupants find thermally acceptable.

In the standard for air quality the rcentage of dissatisfied are based on the "visitors," i.e., people who are entering the room. This is necessary because people generally adapt to the indoor air quality, especially with regard to body odors; there is less adaptation to tobacco smoke and pollutants from building materials (8). In the case of the thermal environment, the guidelines are based on the occupants' perception of comfort. It is interesting to note that both standards recommend a satisfaction criteria of 80% and recognize that there are significant differences in individual perceptions. In other words, some people are very sensitive both to the thermal environment and to indoor pollution, and it is not possible to specify an environment where everybody will be satisfied.

Indoor Air Quality and Ventilation

Because there are some gaps in our knowledge of dose-response to indoor air pollution, ASHRAE 62-89 ves methods for estimating the re-uired level of fresh air.

In the first method, the Ventilation Rate Procedure, amounts of fresh air, specified as either cubic feet/minute (cfm) per person or cfm square feet, are given for different types of rooms. It is assumed that this dilutes any air pollutant to a level which will not be harmful or cause any discomfort. In other words, acceptable air quality is achieved by providing a specified quality and quantity of ventilated air to the space in question.

In the second method, the Indoor Air Quality Procedure, acceptable air quality is achieved by controlling known and specifiable contaminants within the space. In other words, the amount of fresh air that will bring the concentration of any pollutant below recommended limit values is calculated. The standard lists amounts for some pollutants, but more knowledge is needed to do so for others. If no better information is available the recommendation is to use the criteria r outside air or 1/10 of the TLV lues.

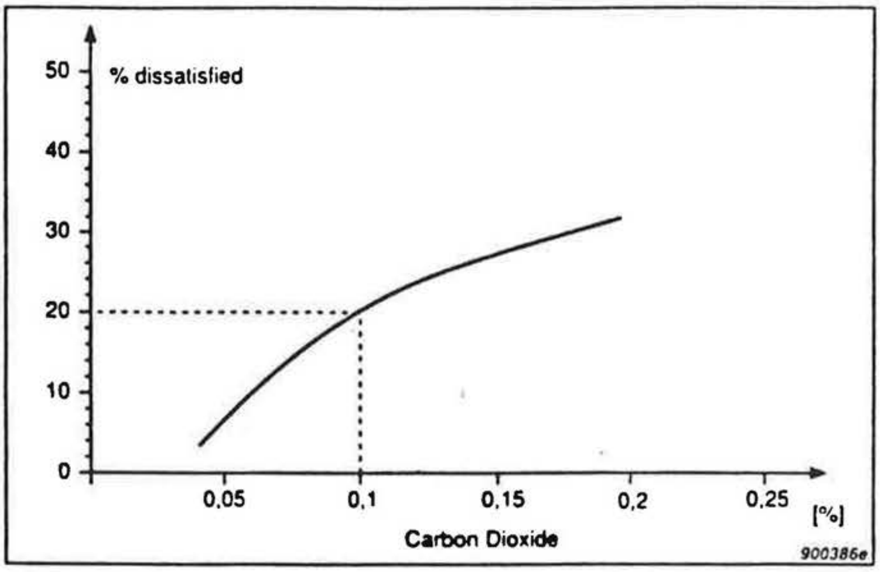

Figure 1: Dose-response function of bioeffluents using CO^2 as an indicator.

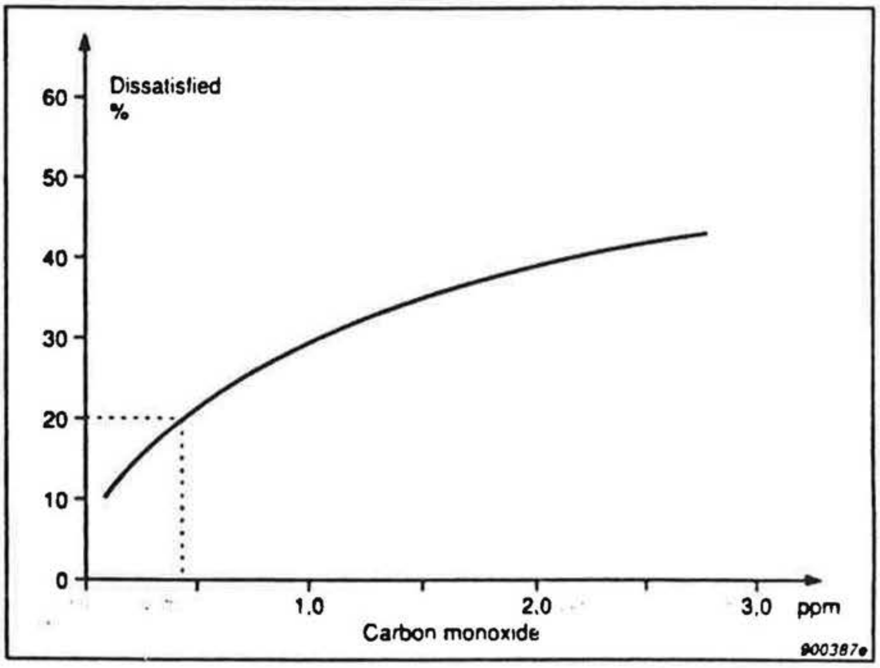

Figure 2: Dose-response function of tobacco smoke using CO as an indicator based on odor.

Body Odor

Human beings emit a large variety of bioeffluents (e.g., from sweat and respiration). The best indicator of the concentration of bioeffluents is carbon dioxide (CO^2), which people emit in large quantities through respiration. Carbon dioxide itself is odorless and harmless in the concentrations usually found in the indoor climate. Many experiments have been performed to establish the relationship between bodily emissions (CO^2) and occupant comfort (14). Figure 1 shows the relationship between the concentration of bioeffluent, expressed by the CO^2 concentration, and visitors' reactions on first entering a room. A 20% dissatisfaction criteria corresponds to a CO^2 level of 1000 ppm (0.1%). This is equivalent to a ventilation rate of 15 cfm per person (8 l/s [liters/second] per person.)

Tobacco Smoke

Another important source of pollution is smoking. The odor is annoying, and, at high concentrations, smoke may irritate the eyes, nose, and throat. The concentration of carbon monoxide (CO) can be used as an indicator of the concentration of tobacco smoke (15). Figure 2 shows the relation between tobacco smoke expressed in ppm of carbon monox-

(Evaluation and Measurement of the Indoor Climate — continued)

ide and the percentage of dissatisfied visitors to a room. A 20% dissatisfaction criteria corresponds to 0.4-0.5 ppm of carbon monoxide. Given normal smoking rates, this corresponds to a supply of fresh air of 40 cfm per person (20 l/s per person.)

Humidity

High humidity can support the growth of organisms like fungi and dust mites. On the other hand, low humidities may increase the risk of catching a common cold and the amount of static electricity or dust in the air. ASHRAE 62-89, therefore, recommends a relative humidity in the middle range of 30-60%.

Volatile Organic Compounds

Although volatile organic compounds (VOC) are probably the most important issue in indoor air quality, existing standards do not yet set requirements. This is because more dose-response studies are needed. Table 1 shows the summary of requirements presented and discussed at the Indoor Air '90 Conference (16).

Outdoor Air Requirements

In ASHRAE 62-89, the outdoor air requirements are typically 15-20 cfm per person (8-10 l/s per person) with 15 cfm per person as a base value.

Assessing the Ventilation System

The listed outdoor air requirements, or the air exchange rates, estimated by the indoor air quality procedures are based on a ventilation system with perfect mixing. This assumption does not always apply. In fact, as illustrated in Figure 3, the flow pattern may vary significantly. It is also necessary to take into account how efficiently the air is distributed throughout the occupied zone. If there are stagnant zones and short-circuiting, the amount of fresh air must be increased. If, on the other hand, it is possible to establish a plug or piston flow (i.e., the old air is pushed out as the new air enters), the amount of fresh air required for efficient ventilation can be reduced.

To properly assess ventilation in the critical breathing zone, (e.g., four feet for sedentary people, six feet for standing people) one must assess three factors: how quickly "old" contaminated air is replaced with "new" fresh air in the occupied zone; how quickly generated contaminants are removed; and how effectively the contaminants are prevented from spreading to unwanted areas such as the occupied zone. The effectiveness of air renewal and contaminant removal are referred to as "air-exchange efficiency," and "ventilation effectiveness," respectively. The air renewal and contaminant removal processes are related but generally not identical, and so must usually be treated separately. However, in spaces where the pollution sources are more or less uniformly distributed, or the sources are difficult to define (e.g., building materials), the air-exchange efficiency may characterize both the air renewal and the contaminant removal process. In either process, one must differentiate between average and local conditions.

Table 1 — Tentative dose response relationship for discomfort resulting from exposure to solvent-like volatile organic compounds.

Total Concentration (mg/m^3)	Irritation and Discomfort	Exposure
<0.20	No irritation or discomfort	The comfort range
0.20-3.0	Irritation and discomfort possible if other exposures interact	The multifactorial exposure range
3.0-25	Exposure effect and probable headache possible if other exposures interact	The discomfort range
>25	Additional neurotoxic effects other than headache may occur	The toxic range

Air-Exchange Efficiency

The definition of air-exchange efficiency is based on the "age" of air in the room, which is a measure of the length of time it has been in the room (Figure 4). The "youngest" air is found where outdoor air comes into the room, and the "oldest" air may be found at any other point in the room. The age of air can be considered in two different ways: the local mean age of air and the room-average age of air.

Local-mean age of air is used in assessing the ventilation of individual work stations or the distribution of air in naturally ventilated buildings. It is also used in mapping airflows through rooms. The advantage of this method is that results apply to individual points within a room — areas of stagnant air can be located, and the ventilation air supply at an individual's work station can be evaluated.

The numbers expressing the average age of room air, also called the room-average age of air, quantifies the performance of a ventilation system. The number takes into account both the amount of ventilation air supplied to the room and the efficiency with which it is distributed around the room.

The average age of room air is measured in the extract air duct. This measurement is, however, not reliable in cases where a large proportion of air leaves the room by other means, for example, through random

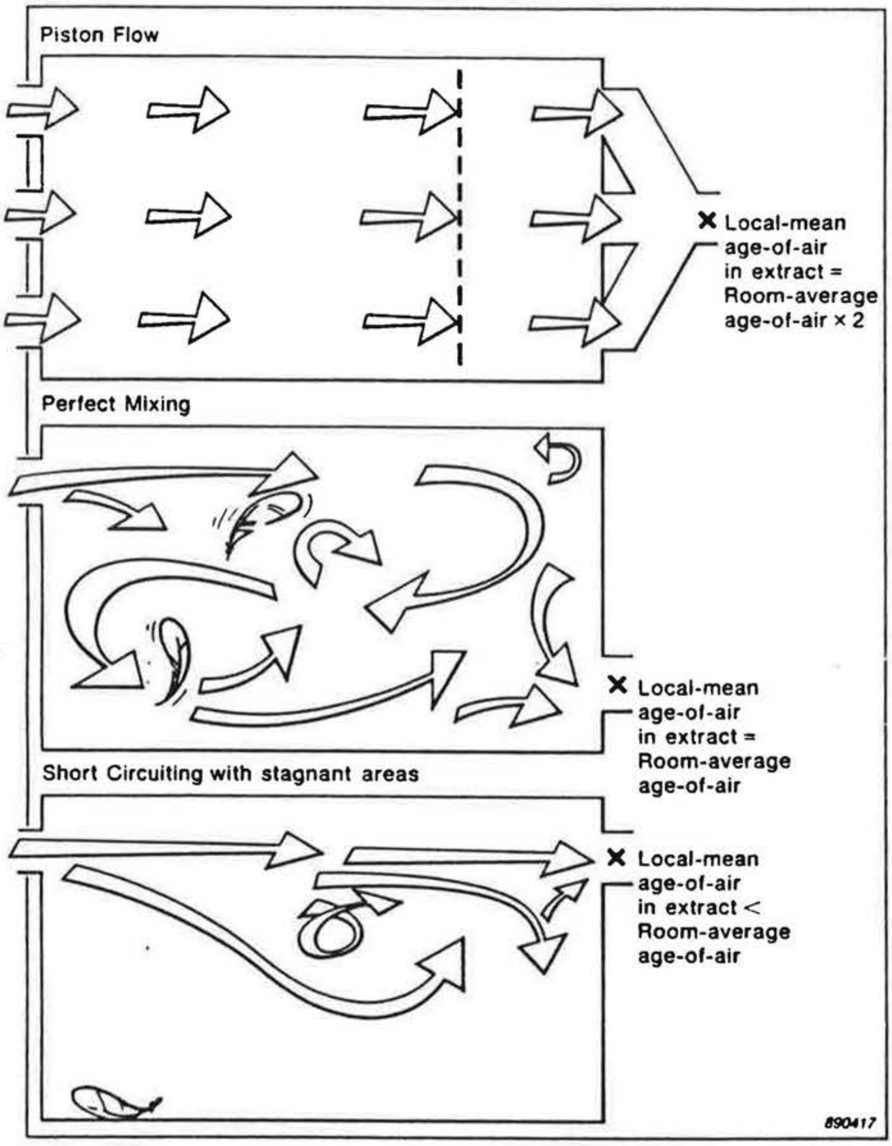

Figure 3: Different ventilation methods.

exfiltration. In these cases the average is calculated as a mean value of the local-age-of-air in different points in the occupied zone. This measure is known as the local-mean age of air.

The efficiency with which ventilation systems exchange room air can be calculated by dividing the local-mean age of air in the extract air duct by the room-average age of air. In a system with perfect mixing (Figure 3) these two values will be equal and the efficiency 1, or 100%. In a perfect piston flow system (Figure 3) the local-mean age of air in the extract air duct is twice the room-average age of air and the efficiency 2, or 200%.

The air-exchange efficiency is, therefore, a function of location and the characteristics of supply and return vents together with temperature and flow rate of the supply air.

Ventilation Effectiveness

One main objective of ventilation is to remove the pollutants generated within a space. The effectiveness of this removal is known as the ventilation effectiveness. A meaningful parameter here is the age of the contaminants in the return-air duct. The age of contaminants is similar to the age of air. The shorter the age, the more effective the removal of the pollutant. This ventilation effectiveness is expressed as the ratio between the nominal time constant for the ventilation of the air and the exit age of the pollutants. If the pollution sources are evenly distributed in the room (e.g., building materials, carpet, people) then the ventilation effectiveness will be similar to the air-exchange efficiency.

Measuring Indoor Air Quality and Ventilation

The discussion of air exchange efficiency and ventilation effectiveness makes it clear that it is often necessary to measure concentrations of individual gases, the air exchange rate, and the efficiency of the ventilation system. Many different techniques, from simple tubes to a sophisticated gas chromatograph, can be used to measure individual gases. The ability to perform real time measurements and monitoring, i.e., measurements over time, is important. The situation in a building is often dynamic so grab samples are not sufficient; measurements over a longer period are also needed to obtain a relevant picture of the conditions. Before the source for the contamination can be determined, the outside conditions must be measured. Measurements of gas concentrations should, in indoor climate investigations, be accompanied by a measurement of the air change rate (i.e., of outside air) from infiltration and/or mechanical ventilation.

Airflow through a room or a building is normally evaluated by using tracer-gas measurements (17). This technique marks the air in a building with something easily identifiable, so that its movement can be traced. The type of tracers used in ventilation measurements are usually colorless, odorless, inert gases not normally present in the environment. The most commonly used tracer gas is sulphur hexaflouride (SF_6). One point worth

Figure 4: The age-of-air concept.

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remembering about tracer-gas measurements is that they can be made in occupied buildings. This is not only much more convenient, but also more accurate, because it takes into account the effect of occupancy on a building's air-exchange rate (e.g., the effect of opening and closing doors and windows). It is, after all, the air-exchange rate of a building under normal working conditions, that is important in most cases.

Results from properly conducted tracer-gas measurements can provide valuable information about ventilation systems, including the amount of outdoor air brought into each room; the efficiency of heat-recovery units; the amount of extract air that is recirculated into the supply-air ducts; the outdoor short-circuit from exhaust to outdoor-air intake; and the distribution of supply air in rooms. Energy loss and many "sick" buildings result from the fact that these parameters were not taken into account in the planning stage of a building and are not measured as part of regular building maintenance checks.

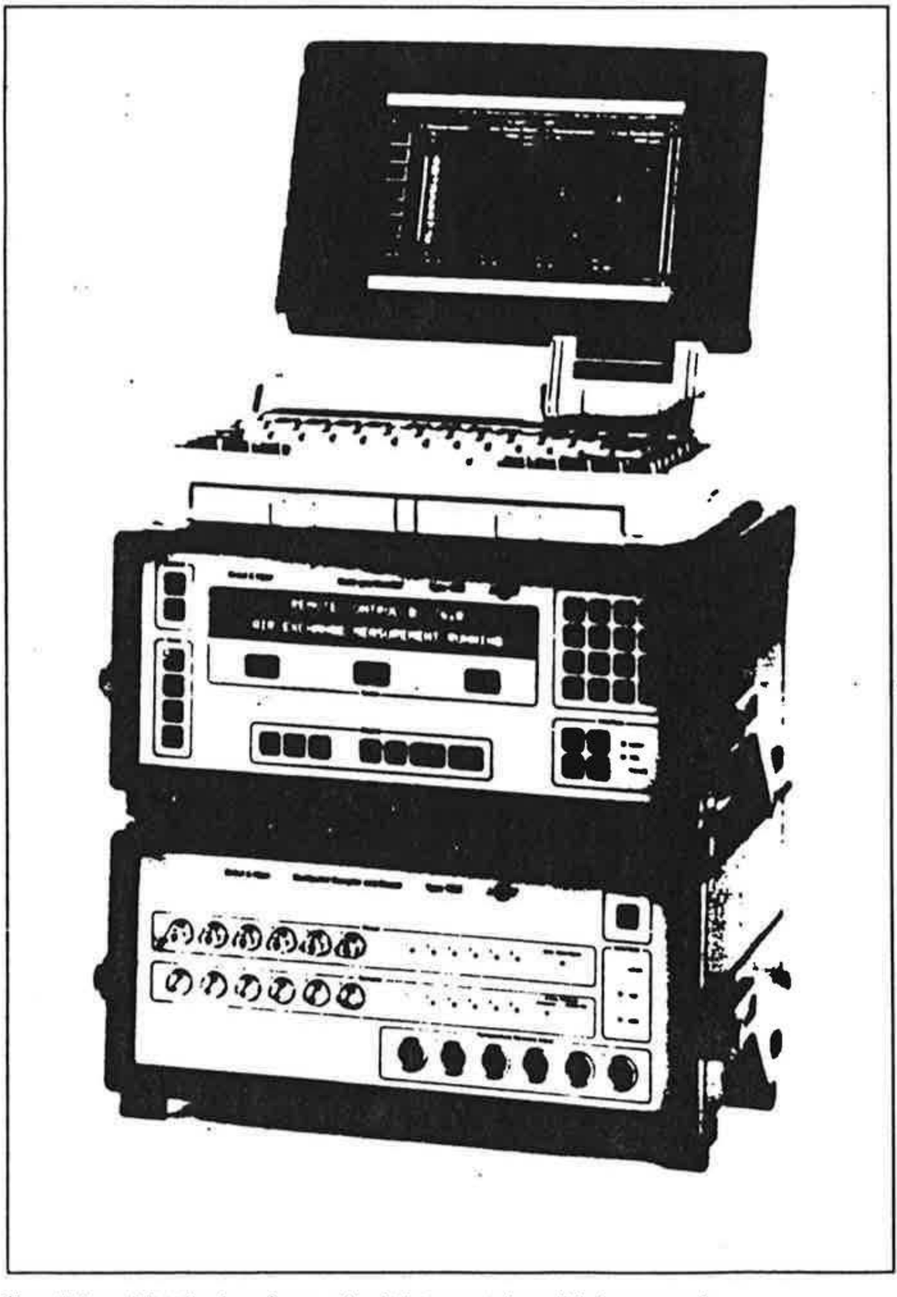

Figure 5 A complete system for performing automatic tracer gas and air pollutant measurements

Tracer-gas measurements are calculated using one of three methods: the concentration-decay method, the constant-emission method, or the constant-concentration method. The concentration-decay method is the most basic method of measuring air-exchange rates. A small quantity of tracer gas is thoroughly mixed into the room air. The source of the gas is then removed and the decay of the concentration of tracer gas in the room is measured over a period of time. The rate of the decay is used as a measure of the air-exchange rate. The only equipment needed for this measurement method is a gas monitor, a bottle of tracer gas and a mixing fan.

The constant-emission method is used for long-term, continuous air-exchange rate measurements in single zones or for measuring airflow through ventilation ducts. When using the constant-emission method, tracer gas is emitted at a constant rate for the duration of the measurement period. While the gas concentration is monitored, the air-exchange rate is calculated from the measured amount of "dosed" gas and the gas concentration.

The constant-concentration method is used for continuous air-exchange rate measurements in one or more zones. It is particularly useful for conducting an analysis in occupied buildings. When using a constant-concentration measurement method, concentrations of tracer gas in a zone are measured by a gas monitor. This information is then sent to a computer that controls the amount of tracer gas "dosed" into the zone to keep this concentration constant. The air-exchange rate is directly proportional to the tracer-gas emission rate required to keep the concentration constant.

This last method offers two significant advantages. First, it can be used to obtain an accurate, long-term, average air-exchange rate in situations where the air-exchange rate varies (e.g., in occupied buildings). Second, it can be used to document these variations in detail. The constant-concentration method is also particularly well suited for continuous measurements of outside-air infiltration into each individual room in a building.

Tracer-gas techniques are also used to measure the age-of-air in, and to

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evaluate the efficiency of, the ventilation system. With the tracer-gas concentration-decay method, the air in the room is marked with tracer gas; then the decay of the gas concentration, due to the infiltration of unmarked outdoor air into the room, is studied. The local-mean age of air is simply the area under the concentration-versus-time curve. This method is preferred by many researchers because it avoids the difficulty of attempting to mark air being introduced into the system. The concentration-decay method is the only method that can be used in a naturally ventilated space. Another method uses the step-up tracer-gas concentration. Here, the tracer gas is dosed into the supply air, and the increase of the gas concentration in the occupied zone and in the extract duct is measured.

It is also worth noting that if the point at which the change in concentration has been studied is in the extract air duct, then the room-average of air can also be calculated without running tests in the room itself. We can also calculate the air-exchange rate for the room as a whole (local-mean age of air in extract) and locate any areas of stagnant air in the room by measuring the local-mean age of air at different points.

The thermal environment is actually a combination of air temperature, mean radiant temperature, air velocity, humidity, and two personal factors — clothing insulation and activity level — that influence a person's perception of warmth and coolness.

A complete tracer-gas system is now commercially available. The full system is shown in Figure 5. It consists of a gas monitor, sampler- and doser-unit and a computer. The gas monitor is a stand-alone instrument that can simultaneously measure humidity and up to five different gases. A typical set-up for IAQ measurements would test for carbon dioxide, carbon monoxide, volatile organic compounds, formaldehyde, water vapor and a tracer-gas like sulphur hexaflouride. The instrument is based on infrared absorption and photoacoustic detection. If this instrument is combined with the multipoint (six locations) sampler and doser unit and controlled by a computer, it is possible to perform all types of tracer-gas measurements and, at the same time, perform concentration measurements of indoor/outdoor air pollutants at different locations.

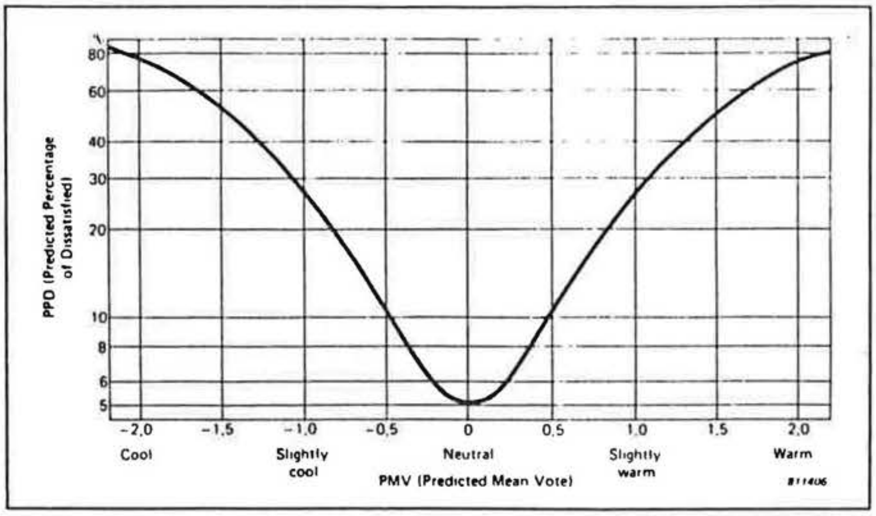

Figure 6: The relationship between PPD (Predicted Percentage of dissatisfied) and PMV (Predicted Mean Vote)

Acceptable Thermal Environment

Most people believe that the quality of the thermal environment can be evaluated simply by measuring the air temperature (i.e., the dry-bulb temperature). This is far from accurate. The thermal environment is actually a combination of air temperature, mean radiant temperature, air velocity, humidity, and two personal factors — clothing insulation and activity level — that influence a person's perception of warmth and coolness.

Often two or more of these factors are combined in a kind of thermal index. The operative temperature, which is used in ASHRAE 55-81R (7), is the mean value between the air temperature and the mean radiant temperature. As in winter, where the outside air temperature and air velocity combine to create a "wind chill" temperature, the indoor air temperature, mean radiant temperature and air velocity combine to generate the "equivalent temperature" (9, 10). The equivalent temperature is more or less the temperature you feel in a space. Take, for example, a summer situation, where the air velocity is increased by a ceiling fan. The air temperature stays the same, but people feel cooler because of the higher air velocity. This can be quantified as a decrease in the equivalent temperature. In a typical winter example, people sitting close to a large window feel cooler than people in the interior zone. The air temperature may be the same both places, but people at the window are exposed to a lower mean radiant temperature, caused by the low window surface temperature. These examples illustrate that the air temperature alone is not sufficient to determine the thermal environment.

The international standard ISO 7730 (11) and ASHRAE's handbook of fundamentals (13) give a method for combining all factors mentioned above into one index number, the Predicted Mean Vote (PMV)-index. The PMV index quantifies the thermal environment on a seven point scale from -3 (cold) to + 3 (hot). The combined influence of the factors can also be expressed as the percentage of occupants who can be expected to be dissatisfied because of a general feeling of warmth or coolness; see the Predicted Percentage of Dissatisfied (PPD) index (Figure 6).

Both ISO7730 and ASHRAE SS-81R recommend guidelines for the

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thermal environment. In ISO 7730, the recommended limits for an acceptable thermal environment are: $-0.5 < PMV < 0.5$ and $PPD < 10\%$.

Figure 7 illustrates the use of recommended limits for a typical winter situation with the heat on and clothing insulations of 1.0 clo (a unit of insulation) and where the occupants have light, mainly sedentary work, or 1.2 met (a unit of activity) such as that found in an office or school. In such a situation, the recommended operative temperature range is 20-24°C. In summer (clothing insulation 0.5 clo) the corresponding interval is 23-26°C. Similar requirements for the operative temperature are given in ASHRAE 55-81R for both winter and summer clothing.

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 an overall thermal neutrality, but may not be comfortable if one part of the body is warm and another cold. Such local discomfort may be caused by an asymmetric radiant field, by a local convective cooling (draft), by contact with a warm or a cold floor, or by a vertical air temperature gradient. A further requirement for thermal comfort, therefore, is that no local warm or cold discomfort exists in any part of the human body.

The sensation of draft is influenced by air temperature, mean air velocity, and air velocity fluctuations. The criteria for the draft sensation is based on a 15% dissatisfaction level. Figure 8 shows that the acceptable air velocity is dependent on the local air temperature and the turbulence intensity of the air velocity.

The criteria for measuring draft sensations are based on the idea that fewer than 10% of the people in a room will be dissatisfied due to the general feeling of warmth and cold (operative temperature, equivalent temperature, PMV-PPD index) and fewer than 5-15% will be dissatisfied due to local thermal discomfort from radiant asymmetry, draft, temperature gradients, or warm or cold floors. On an average it is assumed that, overall, more than 80% will be satisfied.

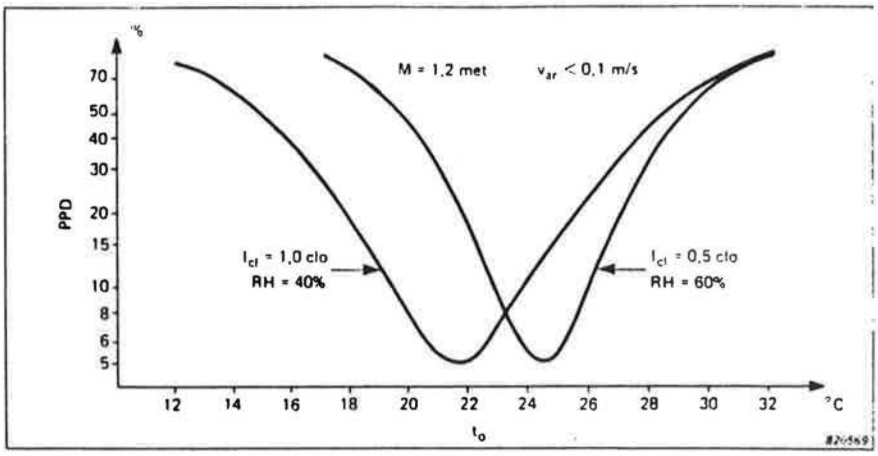

Figure 7: The relationship between operative temperature, To, and Predicted Percentage of Dissatisfied (PPD) for winter (clothing Ici = 1.0 clo) and summer (clothing Ici = 0.5 clo) conditions. Activity, M = 1.2 met, Relative Air Velocity, Var = 0.1 m/s and Relative Humidity RH = 40% in winter and RH = 60% in summer.

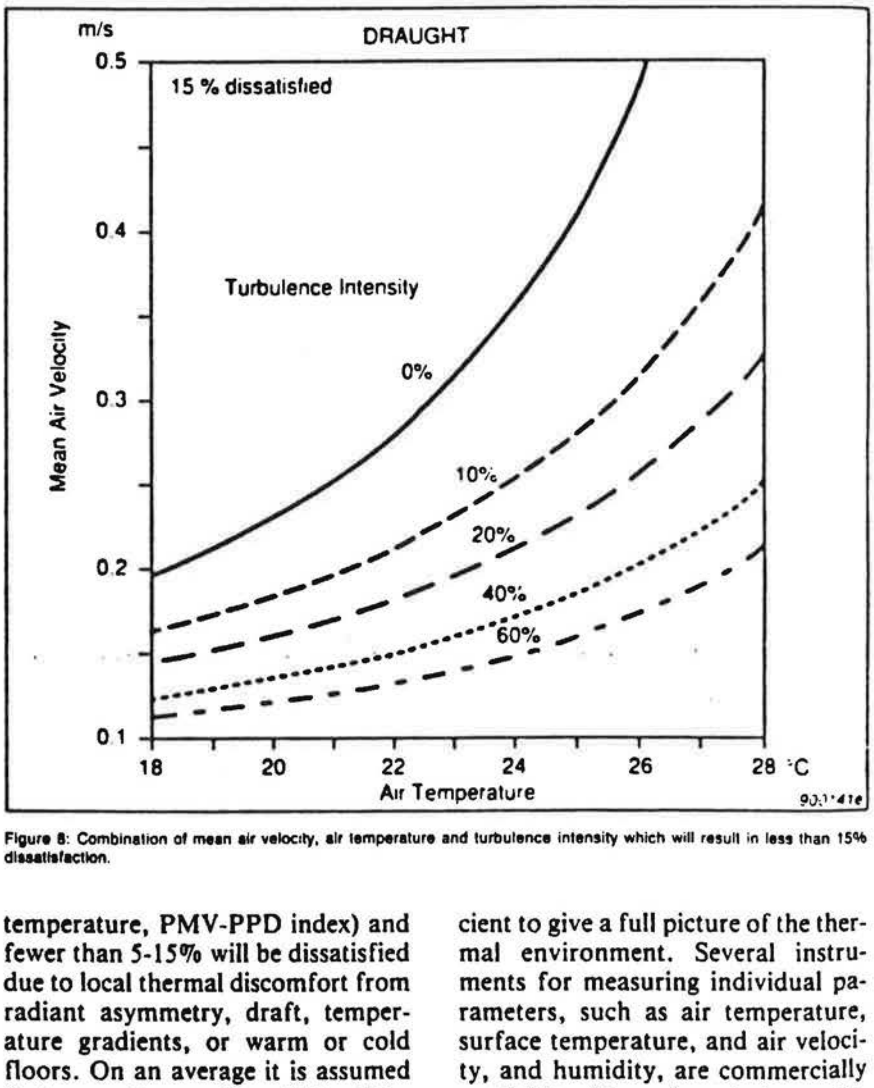

Figure 8: Combination of mean air velocity, air temperature and turbulence intensity which will result in less than 15% dissatisfaction.

Measuring The Thermal Environment

It is clear from the above requirements that a simple measurement of air temperature is not sufficient to give a full picture of the thermal environment. Several instruments for measuring individual parameters, such as air temperature, surface temperature, and air velocity, and humidity, are commercially available. Very few instruments, however, are both sensitive enough to measure the air velocity down to the low levels and fast (i.e., sensitive) enough to measure fluctuations up to 1 Hz. Also, very few instruments can measure the radiant temperature asymmetry directly.

Figure 9 shows an instrument which can measure each of the parameters with an accuracy that fulfills the requirements in ASHRAE 55-81R and ISO 7726 (12). Using the individual parameters one can calculate combined parameters such as operative temperature, equivalent temperature, New Effective temperature (13) and the PMV-PPD index. Another method uses the instrument shown in Figure 10 which has a sensor that measures the combined influence of air temperature, mean radiant temperature, and air velocity, and gives the results as operative or equivalent temperature. If one dials in values for the activity, clothing, and humidity, the instrument estimates PMV-PPD indices for comfort.

Discussion

The indoor environment is complex and cannot be evaluated using only one factor or component. The thermal environment, indoor air quality, and ventilation are closely linked. An increased temperature will make the air seem more stuffy and stagnant and increases the amount of gasses given off by building materials. Increasing ventilation rates may influence both the temperature and air velocity in a space. So while the indoor air quality may be improved, a less comfortable environment may result unless proper engineering controls are applied. Energy consumption should also be considered. But the expense for energy is only a fraction of what an unacceptable indoor climate may cost a company in lost productivity.

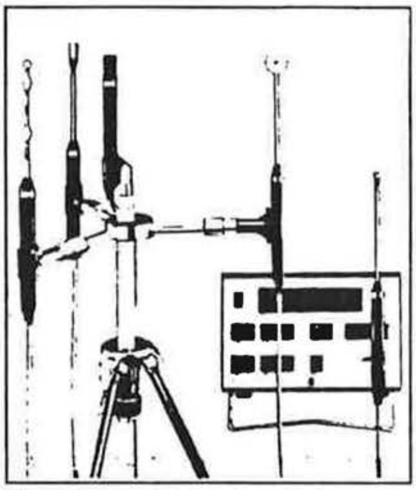

Figure 9 An indoor climate analyzer with 5 sensors for measuring individual thermal parameters (air temperature, surface temperature, radiant temperature, air velocity, humidity)

The answers lie in taking measurements. Measurements by themselves do not solve problems, but they are essential to document objectively what the problem may or may not be. Measurements also help in identifying the cause of the problem and lead the way to a more objective discussion on problems and solutions. Measurements also must be taken after an improvement has been made to document any changes in the physical environment. All of these measurements require reliable and accurate instrumentation, where the measured values are not influenced by the subjective judgment of an operator. ☐

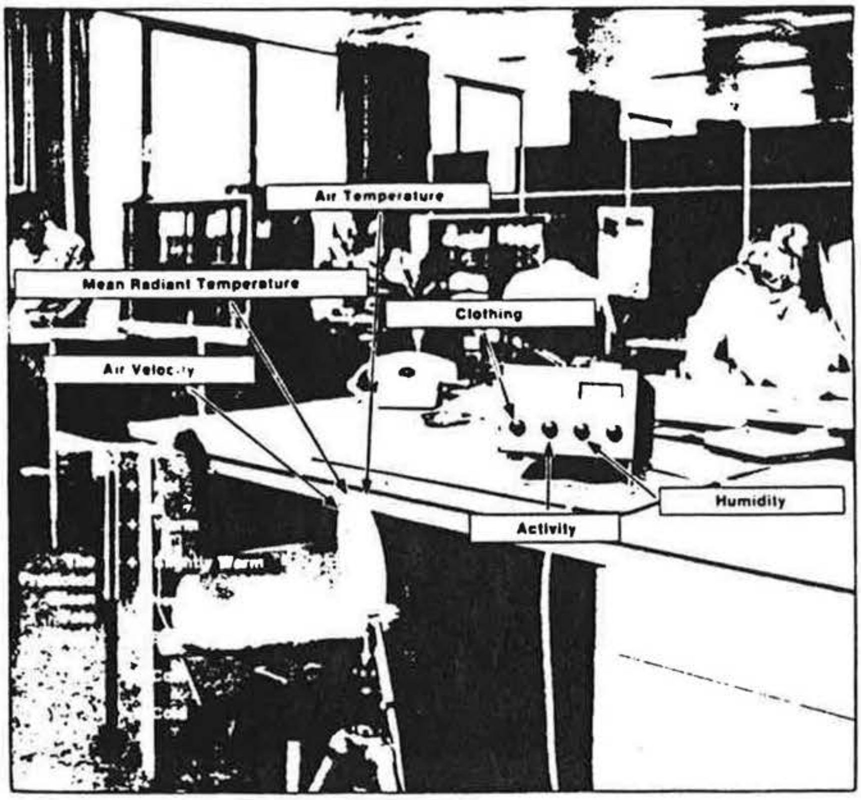

Figure 10 A thermal comfort meter for measuring the combined influence of all 6 thermal parameters

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