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Comparison between Operative and Equivalent Temperature under Typical Indoor Conditions

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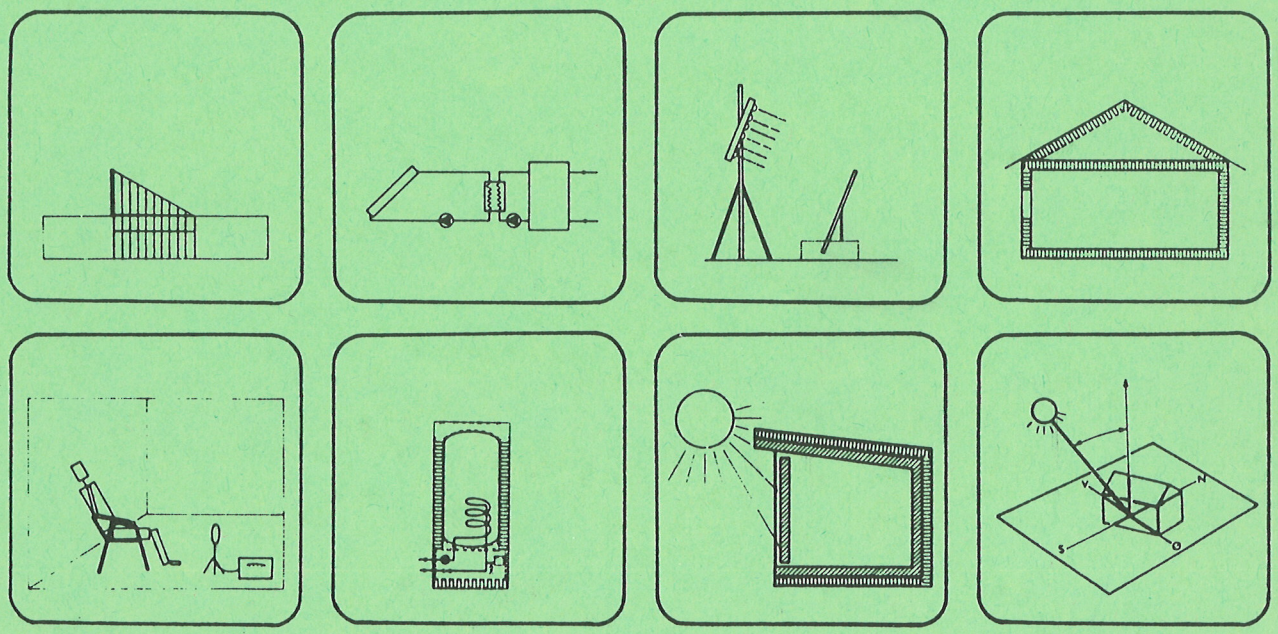

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ABSTRACT

In some of the new standards for thermal environments a certain operative temperature range is given as a requirement for the thermal environment. In other standards the requirement is given as an interval for the PMV-index. This index takes the activity level, clothing, air humidity and the equivalent temperature into account. In this paper it is descussed whether the operative temperature is satisfactory or the equivalent temperature should be used as a better expression because it also takes the air velocity into account. It is shown that the use of the equivalent temperature can save energy during summer conditions but also that it can be necessary to increase the temperature during winter conditions in order to keep the thermal comfort at an acceptable level.

INTRODUCTION

In the ASHRAE standard for thermal environments (ASHRAE 1981) and in the new Nordic Guidelines for Building Regulations (NKB 1981) the requirements for an acceptable thermal environment are given by specifying a range for the operative temperature. This range depends on the actual combination of clothing and activity.

A new draft international standard, ISO/DIS 7730 (ISO 1983), covering the same field of application has been proposed by the International Standard Organization (ISO). In this standard, the requirements for an acceptable thermal environment are given as an interval for the PMV index. The PMV value is an index that predicts the mean value of the subjective ratings of a large group of people on a seven-point scale, ranging from -3 (cold) to +3 (hot), see figure 1. The PMV index takes into account activity level and clothing and four environmental parameters: air temperature, mean radiant temperature, air velocity, and humidity. Thus, it is only necessary to specify one acceptable interval independent of clothing and activity. The recommended interval is $-0.5 < PMV < 0.5$.

As an alternative to the PMV index, ISO gives comfort limits for the operative temperature as a function of activity and clothing. The purpose of this paper is to discuss whether the operative temperature is satisfactory for eva-

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luation of the thermal environment or whether a better expression for the thermal condition is needed, e.g., the equivalent temperature.

OPERATIVE TEMPERATURE AND EQUIVALENT TEMPERATURE

The operative temperature was introduced by Gagge et al. (1937) and has been used ever since in the description of the indoor thermal environment. In all the above-mentioned standards, the operative temperature is defined as the uniform temperature of a radiantly black enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the actual nonuniform environment. The exact equation for the operative temperature is

$$t_o = \frac{h_c \times t_a + h_r \times \bar{t}_r}{h_c + h_r} \qquad (1)$$

where

t_a = air temperature
$\bar{t}_r$ = mean radiant temperature
h_c = heat-transfer coefficient by convection
h_r = heat-transfer coefficient by radiation

A simplified equation for calculation of the operative temperature is given in ISO/DIS 7730:

$$t_o = A \times t_a + (1-a) \times \bar{t}_r \qquad (2)$$

A depends on the air velocity, v_a.

v_a (m/s)	< 0.2	0.2 - 0.6	0.6 - 1.0
A	0.5	0.6	0.7

Similar expressions are given in the ASHRAE standard and the Nordic Guidelines for Building Regulations.

Both the definition of the operative temperature and the expressions (1, 2) can make people believe that the operative temperature takes into account the cooling effect that an air movement has on a heated body like a man. The operative temperature does not do that. It only takes into account the relative influence of the parameters - air temperature, t_a, mean radiant temperature, $\bar{t}_r$, and velocity, v_a - on the temperature of an unheated body.

However, air velocity has a significant influence on the degree of general thermal comfort. Therefore, a temperature index that takes into account the influence of air velocity on the dry heat loss from a person would be suitable. The equivalent temperature is recommended for this purpose. The fourth environmental parameter, air humidity, has only a minor influence on thermal comfort in the range covered by ISO/DIS 7730 and ASHRAE 55-81.

The equivalent temperature is defined as the uniform temperature of an imaginary enclosure with air velocity equal to zero in which a person will exchange the same dry heat loss by radiation and convection as in the actual environment. In other words, the equivalent temperature is the temperature that a person senses in the actual environment.

The equivalent temperature is characterized by the fact that the dry heat loss from a person - thus the degree of thermal comfort - is unchanged for all those combinations of air temperature, mean radiant temperature, and air velocity that give the same equivalent temperature.

The equivalent temperature was first introduced by Dufton (1932), who constructed a special sensor (Eupatheoscope) for measurement of the equivalent temperature. Bedford (1936) proposed the following expression for calculation of the equivalent temperature:

$$t_{eq} = 0.522 \times t_a + 0.478 \times \bar{t}_r - 0.21 \times \sqrt{v_a} \times (37.8 - t_a)\ ^{o}C \qquad (3)$$

Gagge (1940) introduced the standard operative temperature:

$$t_{so} = 0.48 \times \bar{t}_r + 0.52\left[\sqrt{\frac{v_a}{0.076}} \times t_a - (\sqrt{\frac{v_a}{0.076}} - 1) \times t_{cl}\right]\ ^{o}C \qquad (4)$$

where t_{cl} is the mean clothing temperature of the person whose thermal comfort is to be determined. By including the mean clothing surface temperature, the equation takes into account the influence of the clothing on the equiv. temp.

McIntyre (1976) defined the subjective temperature:

$$t_{sub} \quad \frac{0.44 \times \bar{t}_r + 0.56 \times (5 - \sqrt{10v_a} \times (5 - t_a))}{0.44 + 0.56 \times 10v_a}\ ^{o}C \qquad (5)$$

for $v_a \geq 0.15$ m/s and

$$t_{sub} = 0.56 \times t_a + 0.44 \times \bar{t}_r \quad ^{o}C$$

for $v_a < 0.15$ m/s.

Recently, Madsen (1978) has given an equation that includes the influence of the clothing:

$$t_{eq} = 0.55 \times t_a + 0.45 \times \bar{t}_r + \frac{0.24 - 0.75 \times \sqrt{v_a}}{1 + I_{clo}}(36.5 - t_a) \quad ^{o}C \qquad (6)$$

where the last term is included when $v_a > 0.1$ m/s. All these temperatures include the cooling effect of an air movement.

Figure 2 shows how Bedford's, Gagge's, McIntyre's, and Madsen's expressions agree with Fanger's comfort equation (1982). The curve calculated from the comfort equation shows the temperature ($\bar{t}_r = t_a$) that gives the same degree of comfort with air velocity equal to zero as the actual combination of operative temperature and air velocity. It is seen that Bedford's equation gives temperatures too low for small air velocities, while Gagge's, McIntyre's, and Madsen's expressions agree fairly well with the comfort equation.

Figure 3 from (ISO/DIS 7730) gives the optimal operative temperature as a function of clothing and activity. Furthermore, the deviations in operative temperature from the optimal operative temperature that can be accepted to keep the PMV value inside the range $-0.5 < PMV < 0.5$ - are given in the same figure.

Beyond giving limits for the PMV index, ISO/DIS 7730 suggests maximum allowable air velocities and ranges for the operative temperature for light, mainly sedentary activity. During winter conditions, (1.0 clo; 1.2 met) the requirements for the operative temperature and the velocity are:

The operative temperature must be between 20°C and 24°C.

The mean air velocity must be less than 0.15 m/s.

During summer conditions, (0.5 clo; 1.2 met) the requirements are:

The operative temperature must be between 23°C and 26°C.

The mean air velocity must be less than 0.25 m/s.

In figures 4 and 5, the operative temperatures have been chosen so that the PMV value equals -0.5 during winter conditions (assuming 1.2 met, 1.0 clo, 50% RH) and 0.5 during summer conditions (assuming 1.2 met, 0.5 clo, 50%RH). Both cases are for a mean air velocity less than 0.1 m/s. The figures show how the PMV value varies when the air velocity is increased and the operative temperature is kept constant. The variation in the PPD index is also shown. The PPD (Predicted Percentage of Dissatisfied) is an index that predicts the percentage of a large group of people likely to feel thermally uncomfortable, i.e., voting hot (+3), warm (+2), cool (-2), or cold (-3) on the PMV scale. The PPD index is given as a function of PMV in figure 6 from Fanger (1982).

It is seen that if the air velocity is 0.15 m/s during winter conditions, the PMV index drops below -0.5 to -0.65 and the PPD index increases to 15%. If the air velocity is 0.25 m/s during summer conditions, the PMV value drops from 0.5 to 0.2 and the PPD index drops to 6%. This shows that maintaining the same operative temperature for different air velocities can imply a significant deviation from the expected degree of thermal comfort.

Apart from this, figures 4 and 5 show how the operative temperature should vary with the air velocity to keep a constant PMV value (still assuming 1.2 met, 50 RH, 1.0 clo for winter conditions and 0.5 clo for summer conditions). This indicates that during winter conditions it can be necessary to increase the operative temperature by 0.5 - 1°C in ventilated rooms to maintain the PMV value inside the range for an acceptable thermal environment. During summer conditions, one can cool 1-1.5°C less than indicated in figure 3. It is important to remember that it is the operative temperature that determines the energy consumption for heating/cooling buildings.

MEASUREMENT OF OPERATIVE AND EQUIVALENT TEMPERATURE

The easiest way to measure the operative temperature is to use a globe that measures in accordance with equation 1 or 2. However, most globes have a rather high time constant, and one must wait 15-20 minutes before the operative temperature can be read. Another disadvantage is that the globe measures the influence of the mean radiant temperature in relation to a sphere instead of the influence in relation to a person. This is due to the fact that the angle factors and the projected area factors for a sphere are independent of the direction, which is not the case for a person (figure 7 and table 1). In many cases, the difference will be insignificant, which is often the case in new well-insulated buildings with rather small window parts. If the variation in radiant temperature in different directions is large, however, the error from using a globe is significant. The influence of a radiant point source, i.e. high intensity infrared heaters, is four times greater if it is placed in front of or behind a person than if it is placed above the person at the same distance. But the influence on the globe will be the same irrespective of the direction in which the point source is place.

The equivalent temperature is more difficult to determine. This is probably the reason why the equivalent temperature is not used so often as the operative temperature. The equivalent temperature can be calculated after measurements of the air temperature, mean radiant temperature, and air velocity. However, mean radiant temperature and low velocities are difficult to measure with good accuracy.

Another method is to use a sensor that is specially designed for the purpose. The sensor must simulate a person's dry heat loss as precisely as possible. This has been achieved with the sensor shown in figure 8 by a careful choice of the transducer's size, form, position, radiant emission, and surface temperature.

The size has been chosen so that the ratio between the heat loss by radiation and by convection is similar to that of a person. According to Fanger (1982), the effective radiation area of a person is only 0.7 times the total surface area. This means that, compared to the heat loss by convection that takes place from the whole surface, the sensor will lose 1/0.7 = 1.4 times more heat by radiation per unit of surface area than a person. However, the convective heat loss per unit surface area of a heated body increases when the size gets smaller. The size of the transducer has therefore been chosen so that the heat loss by convection is also 1.4 times greater per unit area for the sensor than for a person. The mean radiant temperature and the air temperature thereby get the same weighted influence on the sensor as on a person.

The form of the sensor gives approximately the same projected area factor in the three main axes as a person (table 1). The variation in different directions of the projected area factor for a standing and a seated person is shown in figure 7. On this basis, the form of the transducer has been chosen as an ellipsoid revolution with the area factor f_p = 0.08 parallel to the axis and f_p = 0.28 orthogonal to the axis.

By changing the position of the transducer between vertical and horizontal, the transducer can simulate a person in different situations with respect to the projected area factors. The projected area factors for a man, a globe, and the sensor are given in table 1. To simulate a seated person, the sensor should be directed 30° from vertical.

With the chosen size and form of the sensor, the influence of air temperature and mean radiant temperature on the sensor is approximately the same as their influence on a person. The operative temperature is thus equivalent to the mean surface temperature of the unheated transducer.

The color of the sensor and the emission coefficient have been chosen so that the long-wave radiation for the sensor and for both a naked and a dressed person is alike. For shortwave radiation, the emission depends on the color. Using the same transducer, it is not possible to simulate persons in both light-colored and dark clothes when shortwave radiation is present. With the chosen color (gray), the sensor can simulate naked persons or persons wearing light-colored clothes.

Finally, the surface temperature of the sensor is important for the heat exchange with the surroundings. The surface temperature must therefore correspond to the mean clothing surface temperature of the person that the sensor is simulating. The desired surface temperature is maintained by means of a temperature-independent resistance wire wound round the sensor body. The current through this wire is a measure of the heat loss from the sensor. At the same time, there is a wire evenly wound over the heated part of the sensor body. The resistance of this wire is a measure of the mean surface temperature of the body.

It is possible in a simple way, by means of these two windings, to regulate the current to the sensor so that it gets and maintains a mean surface temperature identical to the mean surface temperature of the person the sensor is to simulate. This is done by a simple proportional control unit that tries to keep the sensor's surface temperature at 36.5°C corresponding to the deep body temperature. However, this proportional control has been made so that the load error ($^{o}C \cdot m^2/w$) equals the heat resistance ($^{o}C \cdot m^2/w$) of the skin plus the actual clothing value for those persons the sensor is simulating. So the "clo value" of the sensor is simply changed by changing the load error of the regulation. When after a short time the sensor is in heat balance with the surroundings, the surface temperature will be equal to the mean surface temperature of a person with an activity level that just brings him in optimal thermal comfort in these surroundings, when he wears clothes with a clo value corresponding to the clo value chosen for the sensor.

If the environment gets colder, the heat loss from the sensor will increase. At the same time, the surface temperature will decrease until a new heat balance has occurred. This corresponds to the person increasing the activity

level to maintain optimal thermal comfort in the colder surroundings. If one increases the "clo value" of the sensor, then both the heat loss and the mean surface temperature will decrease. This corresponds to a person putting on more clothes and at the same time reducing the activity level to maintain optimal thermal comfort in the unchanged surroundings.

When constructing the sensor, great effort was put into making the thermal capacity of the sensor as small as possible. This, plus the fact that the sensor is heated, makes the time constant for measuring the equivalent temperature with the sensor smaller than the time constant for measuring the operative temperature with a globe. This is shown in figure 9 from Madsen (1979). The time constant for the sensor when measuring operative temperature is also smaller than for a normal globe made out of copper. The time constant for a globe may be decreased by using lighter materials with a lower heat capacity.

COMPARISON BETWEEN FANGER'S COMFORT EQUATION AND SENSOR

The relation between Fanger's comfort equation and the equivalent temperature measured with the sensor described above has been studied under well-defined conditions. The measurements took place in a room without windows and outside walls and without ventilation. For the parameters in the room one can assume:

$$t_a = \bar{t}_r \pm 0.5^{\circ}C$$

$$v_a < 0.02 \text{ m/s}$$

A fan with variable speed exposed the sensor to different levels of air velocities. The fan was placed in a quadrangular wind channel in which a stack of parallel tubes was also placed to give a laminar airstream toward the sensor. The air velocity was measured with a low-velocity anemometer. To correct for a temperature rise due to the heat loss from the fan, the operative temperature in the airstream was measured all the time with an unheated sensor.

The results of the measurements can be seen in figure 10, which shows the measured difference between the operative temperature and the equivalent temperature for different air velocities. The curves give the calculated difference between the operative temperature and the equivalent temperature for PMV equal to -1, 0, and +1. The curves have been calculated by finding the necessary temperature ($t_a = \bar{t}_r$) to give a centain PMV value (-1, 0, or +1) when the air velocity is equal to zero. When the velocity is increased, the temperature ($t_a = \bar{t}_r$) necessary to give the same PMV value with the actual air velocity is found. The difference between this temperature and the required temperature for air velocity equal to zero is the difference between the operative temperature and the equivalent temperature for the actual combination of PMV value and air velocity.

DISCUSSION

In the previous section, the use of the operative temperature to describe the influence of the thermal environment on a person has been questioned. A more precise method is to use the equivalent temperature, which is related to dry heat loss from a person. A new type of sensor and measuring principle has been presented, which can measure the equivalent temperature directly and measures the operative temperature more correctly than a globe thermometer. The operative temperature has often been used since it was introduced in the 1930s. Recently, it has been included in new standards on the indoor thermal environment (ASHRAE 1981; NKB 1981, ISO 1983.

When the air velocity is small ($v_a < 0.1$ m/s), it does not matter whether the operative temperature or the equivalent temperature is used to describe the indoor thermal conditions. But for greater air velocities, the operative temperature is less suitable because it does not include the extra cooling effect of the air movements. If the operative temperature is kept constant while the air velocity is increased, the dry heat loss will increase and then the PMV

value will decrease. This drop in the PMV value will not be expressed in the operative temperature, but it will be expressed in the equivalent temperature as shown in figure 2. This is due to the fact that the equivalent temperature takes the cooling effect of an air movement into account.

The windchill index (Siple and Passel 1945) can be mentioned as a parallel to the equivalent temperature. The windchill index is used during the winter to describe the outdoor climate. In this index, air temperature and wind velocity are converted to one temperature, the "Windchill temperature". The windchill index also takes the cooling effect of the air movements into account.

From figure 4 it is seen that an operative temperature, t_o = 20°C, will be satisfactory according to the ISO standard for winter conditions (1.0 clo, 1.2 met) provided the air velocity < 0.10 m/s. This will imply PMV = -0.5. If the air velocity is 0.15 m/s, which is the recommended maximum allowable mean air velocity according to the standard, the PMV value will drop to -0.65. The resulting PMV value is outside the recommended range, although each parameter is inside the range recommended for it. This means that the number of persons dissatisfied due to a general sensation of cold will increase and, as a result of this, the number of people dissatisfied due to draught will also increase. Thus, the occupants will demand an increase in the operative temperature, which again will result in higher energy consumption. So in wintertime it is very important to keep air velocities very low. An equivalent temperature of 20°C will always provide the same general thermal sensation and number of dissatisfied, but the number of persons dissatisfied due to draught may increase even if the equivalent temperature is constant.

During summertime the PMV value can be held at less than 0.5 by keeping the operative temperature less than 26°C when the air velocity < 0.1 m/s. However, by allowing the mean air velocity to increase to 0.25 m/s, which is the maximum allowable mean air velocity for summertime, the operative temperature may increase beyond 26°C without violating the required PMV < 0.5. In this way, the energy necessary for cooling can be cut down, but increasing the air velocity can imply that the number of people dissatisfied due to draught will increase.

The ASHRAE standard has included an extended summer zone with higher operative temperatures and higher air velocities. The requirements to the operative temperature and the air velocity to ensure -0.5 < PMV < 0.5 cannot be given independently.

If the equivalent temperature is used instead of the operative temperature, it will be sufficient to give one interval for the temperature to ensure -0.5 < PMV < 0.5 when the clothing, activity level, and humidity are maintained.

That the equivalent temperature is a fine temperature to characterize the influence of the thermal surroundings on the occupants is emphasized by the accordance between the equivalent temperature calculated from Madsen's, McIntyre's, or Gagge's expressions and the comfort temperature from Fanger's comfort equation (figure 2). It should be mentioned that it is not possible to give a simple analytical expression for calculation of the equivalent temperature as it is defined. The given expressions are only approximations. The equivalent temperature may be estimated from Fanger's equation for the PMV value (Fanger 1982).

In figure 10 it is shown how well the described comfort transducer is able to measure the equivalent temperature directly. Even though the sensor only approximates the dry heat loss from a person to some extent, it measures the equivalent temperature as this is defined. Beyond measuring the equivalent temperature in accordance with the influence of the air temperature, mean radiant temperature, and the air velocity on the dry heat loss from man, the sensor is an improvement compared to a globe for measuring the operative temperature. This is due partly to the better simulation of the radiant heat exchange for a person (projected area factor, color) and partly to the lower time constant compared to a globe, which is normally made of copper.

From figure 10 it is also seen that by measuring the operative temperature and the equivalent temperature it is possible to get an estimate of the mean air velocity. Due to the time constant, it is not possible to register the fluctuations of the air velocity, which often occur in ventilated spaces (Thorshauge 1982). These fluctuations may increase the sensation of draught, as shown by Fanger and Pedersen (1977). But the influence of the air velocity and its fluctuations on the dry heat loss is taken into account by using the described sensor. So it is possible to get a good estimate of the air velocity as it influences the dry heat loss and thus the general thermal sensation.

The evaluation of ceiling fans is a very common case where the use of the equivalent temperature is recommended. In summer, ceiling fans are used for cooling by increasing the air velocity. It may be difficult to get a feeling of the cooling effect if it is described as a combination of operative temperature and air velocity. If one instead describes the cooling effect by the equivalent temperature, it will be given directly in degrees. First, the equivalent temperature is measured with the fan turned off and next with the fan on. The difference is the cooling effect in degrees, i.e., the number of degrees one can increase the thermostat setting of the air conditioner in summer.

In winter, ceiling fans are often used, especially in industries, to bring down the warm air at the ceiling in the occupied zone to save heating. If one uses the operative temperature to evaluate the benefit (i.e. increase in temperature) of this arrangement, one may draw some false conclusions, because the ceiling fan may also increase the air velocity in the occupied zone. The cooling effect of this increase in air velocity may outbalance the heating effect of the increase in temperature. The end result is then zero or even more energy may be used by running the fan. If, however, the equivalent temperature is used to evaluate the effect, both the increase in temperature and the increase in air velocity are taken into account. This means that the equivalent temperature shows directly if it is an advantage to use the ceiling fan and how great the benefit is.

CONCLUSION

The use of operative temperature and equivalent temperature to describe the thermal environment and its influence on the occupants has been compared and discussed.

The operative temperature is a good one to use when evaluating the heating and cooling loads of a room or building, but it is only useful for describing the general thermal comfort at air velocities < 0.1 m/s.

The equivalent temperature is more correct, even at higher air velocities, because it takes into account the total dry heat loss from a person, i.e., it measures the integrated influence of air temperature, mean radiant temperature, and air velocity. A sensor for measuring the equivalent temperature directly has been described.

The general thermal comfort may be described more correctly and accurately by using an index like PMV or by using the equivalent temperature than by using the operative temperature alone. Only then is it possible to minimize the expenses for heating and air-conditioning buildings without sacrificing an acceptable thermal environment.

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		Up/Down	Right/Left	Front/Back
Standing	Person	0,08	0,23	0,35
	Comfort Transducer	0,08	0,28	0,28
	Sphere	0,25	0,25	0,25
Sitting	Person	0,18	0,22	0,30
	Comfort Transducer	0,18	0,22	0,28
	Sphere	0,25	0,25	0,25

Table 1
Comparison between the Projected Area Factor for Man, Sensor, and Globe in Standing and Seated Position

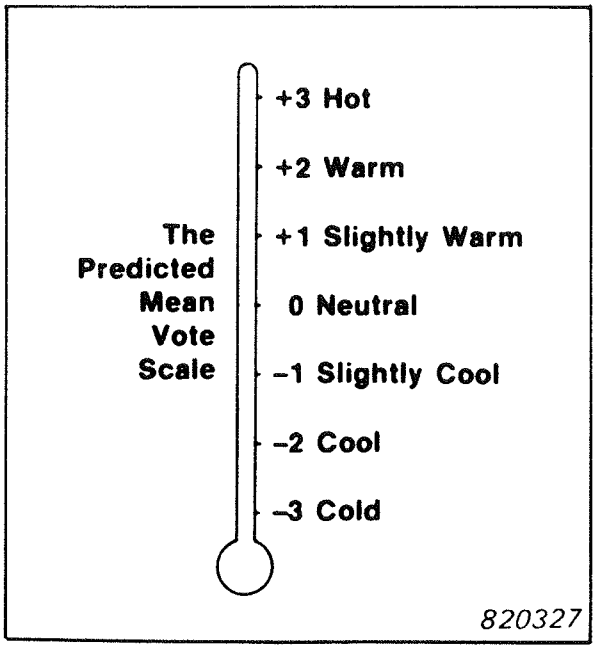


Figure 1. The seven-point scale for thermal sensation

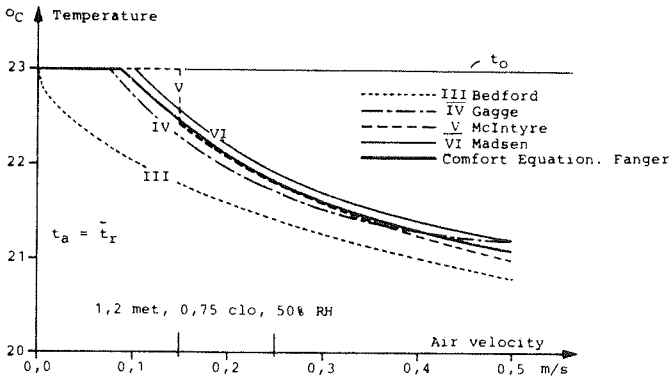


Figure 2. The Dependence of the equivalent temperature on air velocity according the equations III,IV,V,and VI. Calculated equivalent temperatures are compared to an equivalent temperature calculated from Fanger's comfort equation.

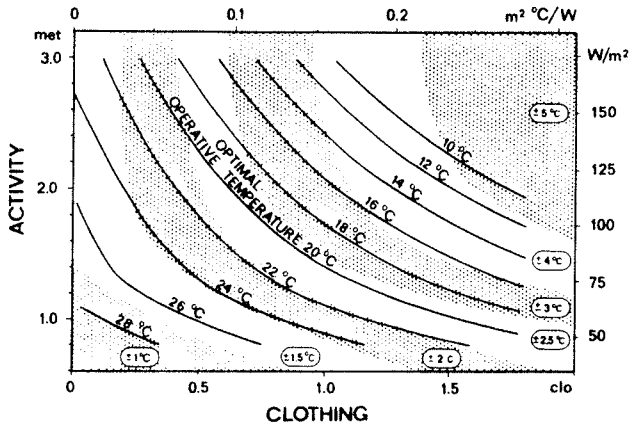


Figure 3. Optimal operative temperature (corresponding to PMV=0) as a function of activity and clothing. Shaded areas indicate comfort range ±Δ t around the optimal temperature inside which -0.5 < PMV < 0.5. Relative air velocity caused by body movement is estimated to be zero for M < 1 met and V_a = 0.3 (m-1) for M > 1 met. Relative humidity is 50%.

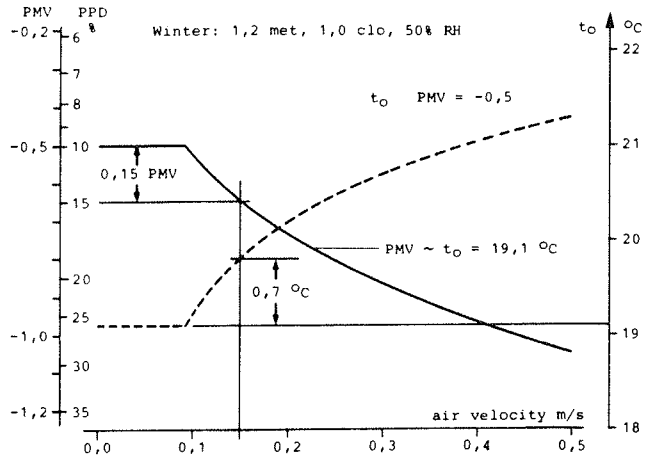


Figure 4. Variation of PMV when air velocity is increased and operative temperature is unchanged for winter conditions (1.2 met, 1.0 clo, 50% RH). Necessary increase in operative temperature to ensure constant PMV of -0.5 for increase in air velocity is also shown.

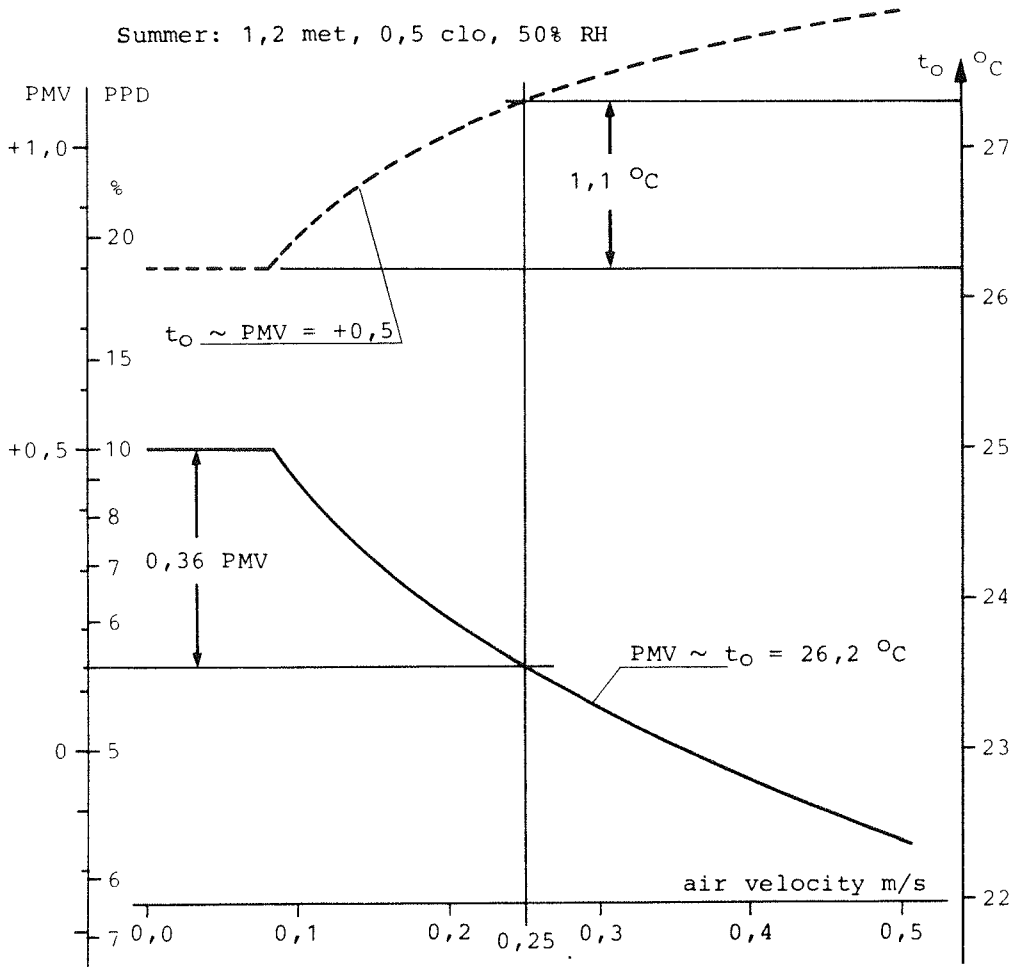


Figure 5. Variation of PMV when air velocity is increased and operative temperature unchanged for summer conditions (1.2 met, 0.5 clo, 50% RH). Allowed increase in operative temperature without violating requirement of PMV < 0.5, when air velocity is increased, is also shown.

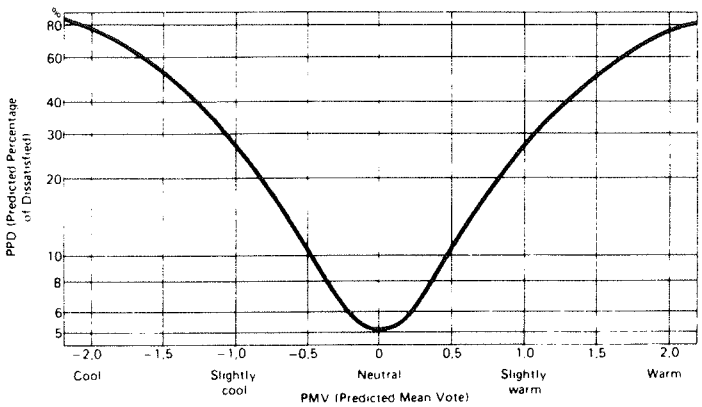


Figure 6. Relation between PMV index and PPD index (taken from 10)

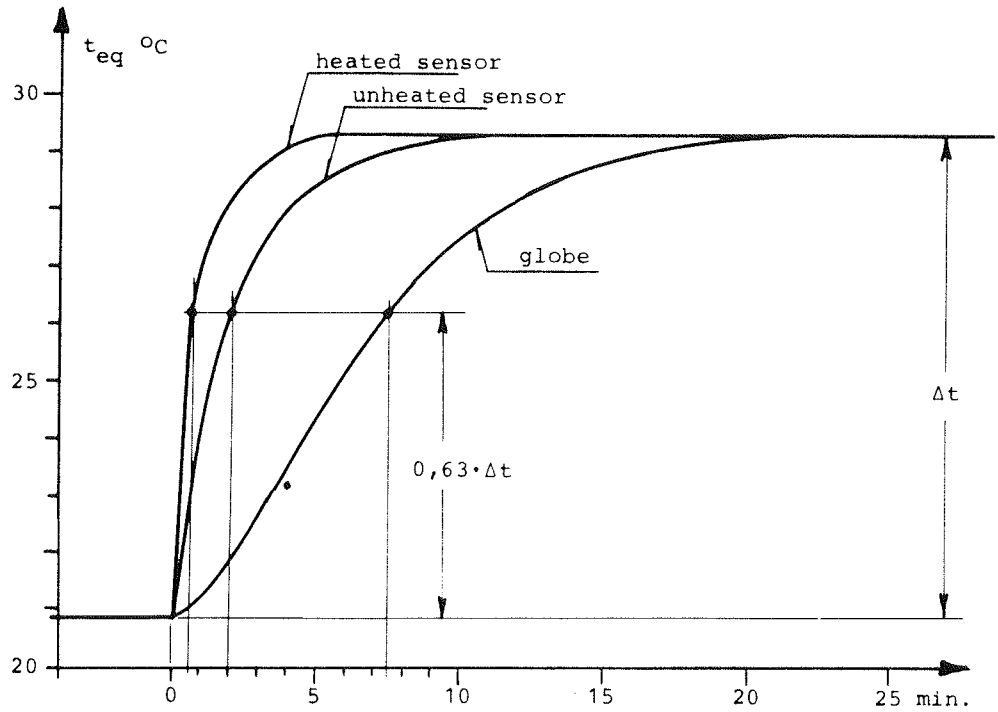


Figure 9. Temperature history and time constand for globe and comfort sensor respectively at an instantaneous change of mean radiant temperature t_r. (From Madsen, T.L., 1977)

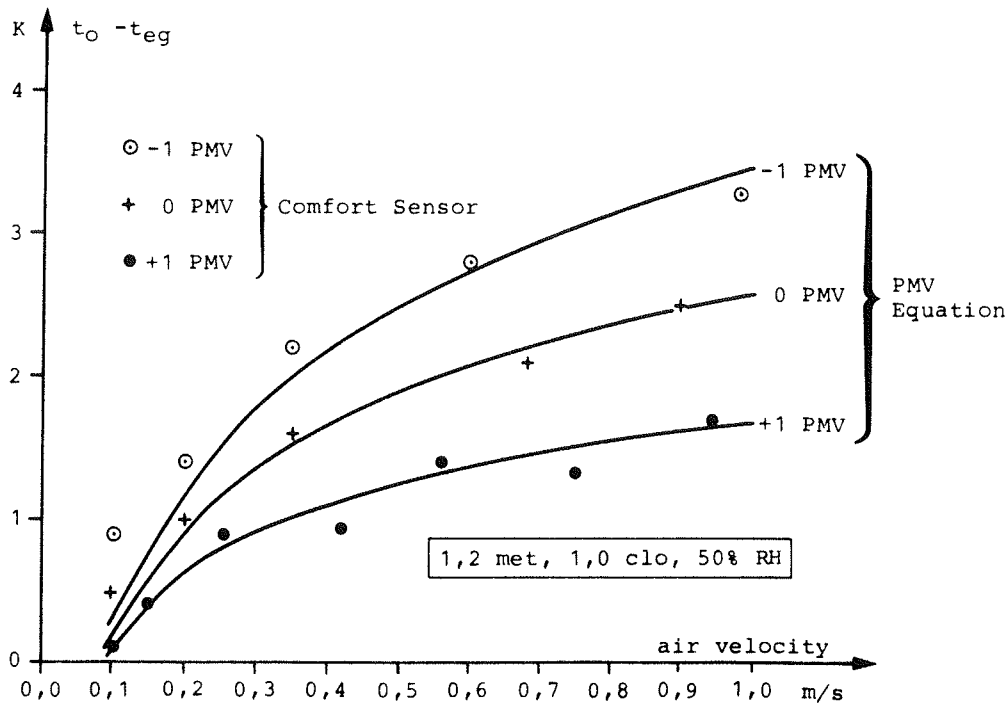
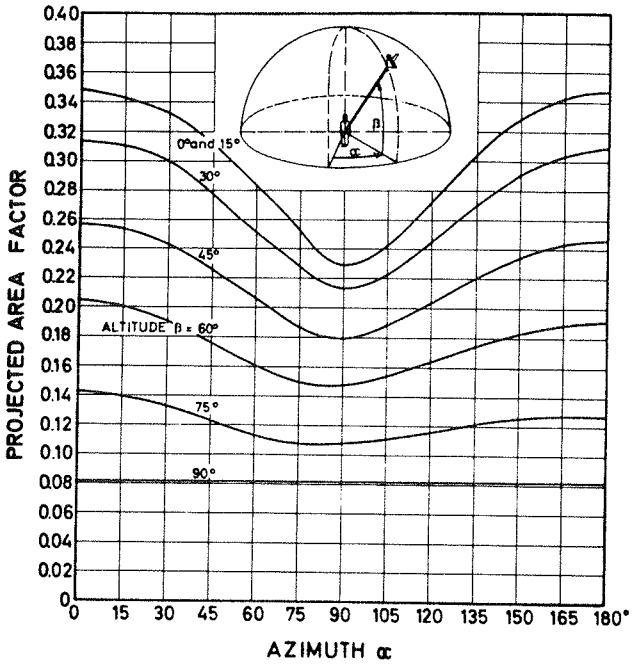
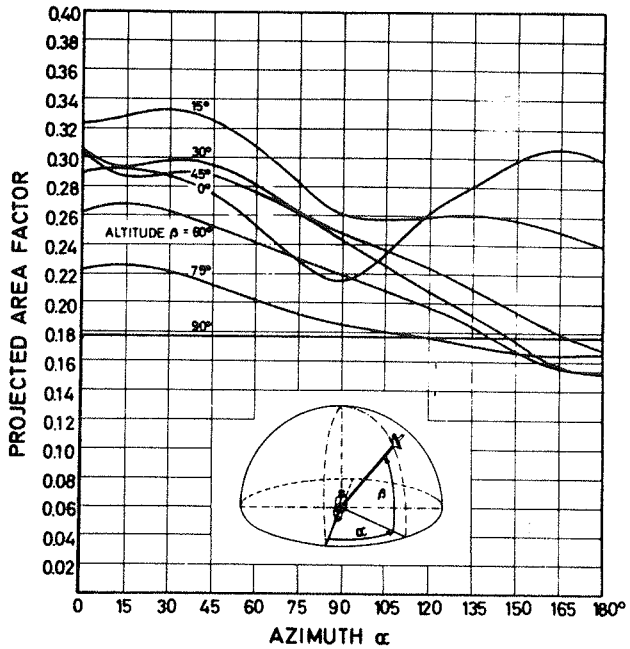


Figure 10. Difference between operative temperature and equivalent temperature for different air velocities. Curves show the calculated differences keeping PMV value constant. Plotted points are values measured with comfort sensor in conditions giving same constant PMV values.



Projected area factor for standing persons, nude and clothed.



Projected area factor for seated persons, nude and clothed.

Figure 7. Projected area factor for standing and seated persons nude and clothed.

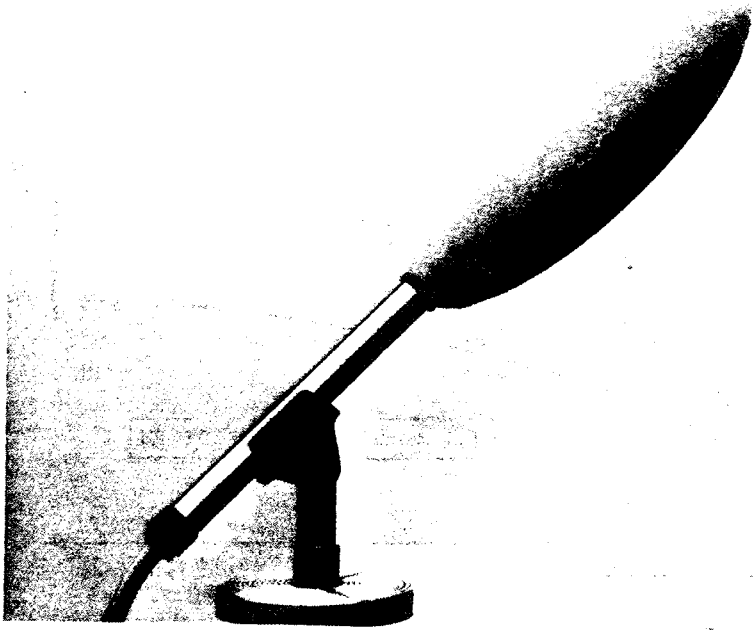


Figure 8. The sensor. Direction of the sensor can be changed to simulate a person in standing, seated, or lying position.