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INVITED PRESENTATION 1

HOW TO MEASURE MEAN RADIANT-, OPERATIVE- AND EQUIVALENT TEMPERATURE CORRECTLY

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INTRODUCTION

The most common measure of the thermal environment is air temperature. To evaluate the influence of the thermal environment on man, it is necessary to take into account three other environmental parameters, mean radiant temperature, air velocity and humidity, together with the two individual factors clothing and activity. The influence of the mean radiant temperature on the heat loss from a person is as important as the air temperature; but often the mean radiant temperature is neglected due to the difficulties of measurements.

In moderate thermal environments the three most significant environmental parameters for man's heat exchange air temperature, mean radiant temperature and air velocity is combined in one temperature index like operative temperature or equivalent temperature.

The present paper will describe how mean radiant-, operative and equivalent temperature is measured. The use and interrelation between these parameters will also be discussed.

MEAN RADIANT TEMPERATURE

Mean Radiant Temperature ($\bar{t}_r$) is defined as the uniform temperature of an enclosure in which an occupant would exchange the same amount of radiant heat as in the existing non-uniform environment. It is important to note that the mean radiant temperature is defined in relation to the human body and then also depends on the body position (standing, seated). Furthermore, the geometry of the room, position in the room, temperature and emittance of surrounding surfaces will influence the mean radiant temperature. The mean radiant temperature may then be calculated when knowing surface temperatures and angle factors, which take into account the shape, size and relative position of a given surface and can be estimated by figures given by Fanger [1982] and ISO 7726 [1985].

Very few commercially available instruments exist for measuring the mean radiant temperature, which is one of the reasons why people do not often take it into account.

In general there are three methods for measuring/estimating the mean radiant temperatures

1. Measurement of surface temperature and calculation by the use of angle factors
2. Measurement of plane radiant temperature and calculation by the use of projected area factors
3. Measurement of "globe" temperature, air temperature, and air velocity and the calculation of the mean radiant temperature.

All three methods have been introduced in existing standards for measurement of the thermal environment ASHRAE 55-81 [1981], ISO 7726 [1985].

The mean radiant temperature may be calculated from the plane radiant temperature, t_{pr}, in six directions (up, down, left, right, front, back) weighed by the projected area factors of a person in the same six directions (Table 1).

Table 1. Projected area factors for a person, ellipsoid (comfort transducer) and a sphere. In the case of the ellipsoid shaped sensor (Fig. 3) it is inclined 30° when simulating a seated person

		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

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When the direction of the person is not known a mean weighting coefficient for right-left and front-back is used. Then the mean radiant temperature may be estimated as:

Standing person

$$\bar{t}_r = 0{,}060\ (t_{pr}[\mathrm{up}] + t_{pr}[\mathrm{down}]) + 0{,}220\ (t_{pr}[\mathrm{right}] + t_{pr}[\mathrm{left}] + t_{pr}[\mathrm{front}] + t_{pr}[\mathrm{back}]) \quad (1)$$

Seated person

$$\bar{t}_r = 0{,}127\ (t_{pr}[\mathrm{up}] + t_{pr}[\mathrm{down}]) + 0{,}186\ (t_{pr}[\mathrm{right}] + t_{pr}[\mathrm{left}] + t_{pr}[\mathrm{front}] + t_{pr}[\mathrm{back}]) \quad (2)$$

By this method the mean radiant temperature is calculated by means of radiant vectors in the six main directions weighted according to the respective projected area factors for a standing or seated person.

Measurement of "globe" Temperature

The most common method to measure mean radiant temperature is to use a black globe thermometer (Vernon [1932]).

Natural convection ($v_a < 0{,}05\ |t_g - t_a|^{0.42}$)

$$\bar{t}_r = \left[(t_g + 273)^4 + 0{,}4 \cdot 10^8\, |t_g - t_a|^{0.25} \cdot (t_g - t_a) \right]^{1/4} - 273\ °C$$

Forced convection ($v_a \geqslant 0{,}05\ |t_g - t_a|^{0.42}$)

$$\bar{t}_r = \left[(t_g + 273)^4 + 2{,}5 \cdot 10^8\, v_a^{0.6}\, (t_g - t_a) \right]^{1/4} - 273\ °C$$

Linear equation $|t_g - t_a| < 20°C$

$$\bar{t}_r = 2{,}2\ \sqrt{v_a}\,(t_g - t_a) + t_g \quad °C$$

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Fig. 1. Formulae for estimating the mean radiant temperature by means of a standard globe thermometer (diameter = 0,15 cm, emissivity = 0,95)

The black globe can in theory have any diameter, but very often a diameter of 0,15 m is used. Equations for a standard globe (0,15 m) are shown in Fig. 1 (ISO 7726 [1985]). It should be noted that the smaller the diameter of the globe, the greater the effect of the air temperature and air velocity, thus causing a reduction in the accuracy of the measurement of the mean radiant temperature. Fig. 2 shows the relative influence of air temperature and mean radiant temperature on the globe temperature. The sphere shape of a globe and the black colour do not really represent the shape of a human being (Table 1) and the normal colours of clothing. An ellipsoid shaped "globe" (Fig. 3) with projected area factors as shown in Table 1 may be considered a closer approximation of the shape of the human body. The projected area factor is estimated as A_{pr}/A_r where A_{pr} is the surface area projected on one direction and A_r is the total radiant surface area. This factor is related to shape of a person or a sensor and indicates the relative importance of the radiation from different directions.

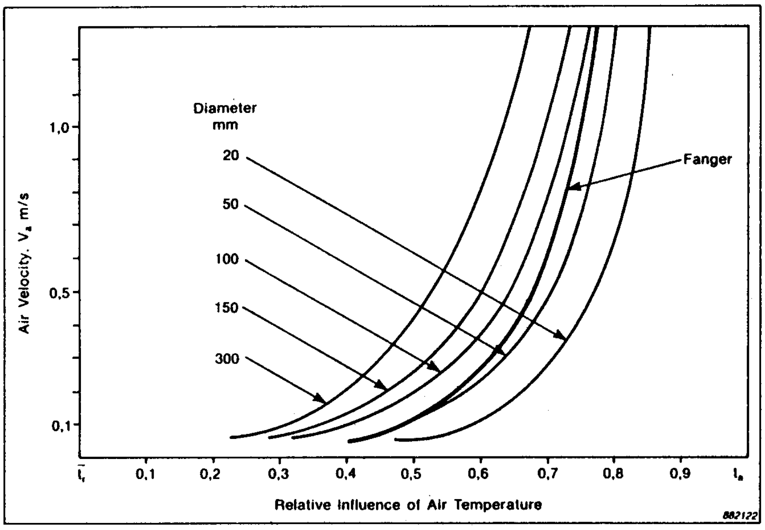

Fig. 2. The figure shows the relative influence of air temperature, t_a, and mean radiant temperature, $\bar{t}_r$, on a globe. The influence depends on the globes diameter and air velocity. For a 100 mm globe, and an air velocity = 0,4 m/s the globe temperature, $t_g = 0{,}6 \cdot t_a + (1 - 0{,}6) \cdot \bar{t}_r$

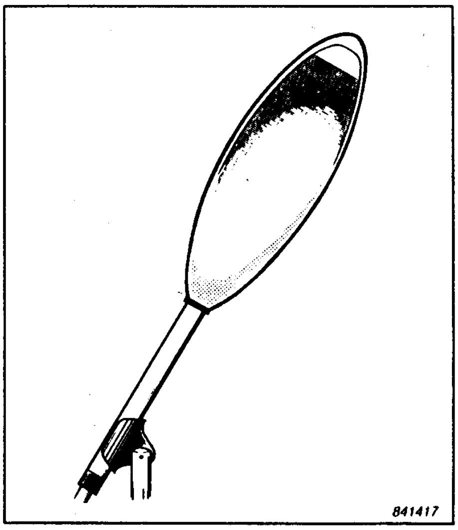

Fig. 3. An ellipsoid shaped sensor

The inclination of the axis of the ellipsoid depends on the position of the subject: standing, axis vertical; seated, axis inclined at 30°. This sensor, (Madsen et al. [1976, 1984]) consists of a light, foam material covered with a resistance thread for measurement of the mean surface temperature.

The use of a black "globe" thermometer in the case of exposure to short wave radiation (for example the sun) will result in an over-estimation of the effect of the radiation. In this case it is better to use a "globe" with a medium grey colour, which better simulates the absorbtivity of a clothed person.

COMPARISON OF DIFFERENT METHODS FOR MEASURING THE MEAN RADIANT TEMPERATURE

In a study by Olesen et al. [1989] the different methods listed above for measuring the mean radiant temperature were studied.

The results showed that the difference between the three methods were relatively small (less than 1°C) for environments with relatively uniform surface temperature distribution. But for environments with a single radiant source there may be considerable differences. Table 2 shows the results from a case where a person is exposed to only one radiant source positioned above the head (Fig. 4). For this more extreme case the difference is much greater than for the other cases with evenly distributed radiant sources.

The sphere in particular will over-estimate the radiation from a source above the head of a person with up to 8,9°C.This difference is found for a standing person under a high ceiling, 10 m and a radiant source with a surface temperature equal to 800°C. This would also be expected from the projected area factors shown in Table 1. Also for a sedentary person in this space the radiant heat from the ceiling is over-estimated by a sphere (4,5°C). For a radiant source closer to the person (i.e. higher angle factor) the sphere will also over-estimate the radiation on a seated (0,5 – 1,8°C) and a standing person (1,4 – 5,4°C). Both the use of a ellipsoid shaped sensor and the use of a weighted mean of the plane radiant temperature in six main directions give a much better approximation to the mean radiant temperature than the sphere shaped globe.

Also the influence of the colour of a sensor for measuring thermal radiation was studied. In a test set-up (Fig. 5) three ellipsoid-shaped sensors with different colours (white, grey, black) were exposed to sunlight. The direction of the sunlight was, in one test, from the side of the sensors and in another test from the top. In both cases the radiant level was 800 W/m^2, air temperature equal to surrounding surface temperatures 21 – 23°C, and air velocity 0,2 m/s. In the test the operative temperature of the sensors were compared. The results are shown in Table 3.

Table 2. Results of the comparison for a rectangular radiant source positioned above the head of a person (Fig. 4)

Case	Source Temp. °C	Seated person: Method: A Person $\bar{t}_r$, °C	B Plane $\Delta\bar{t}_r$, °C	C Sphere $\Delta\bar{t}_r$, °C	Ellipsoide $\Delta\bar{t}_r$, °C	Standing person: Method: A Person $\bar{t}_r$, °C	B Plane $\Delta\bar{t}_r$, °C	C Sphere $\Delta\bar{t}_r$, °C	Ellipsoide $\Delta\bar{t}_r$, °C
2×2 m radiant source 3 m above the floor	60	13,8	−0,1	0,5	−0,1	13,9	0,2	1,4	−0,1
	200	19,1	−0,3	1,8	−0,4	19,5	0,6	5,6	−0,5
4×4 radiant source 10 m above the floor	200	13,6	0,1	1,0	0,5	12,8	0,4	2,1	0,3
	800	18,4	0,7	4,5	2,4	15,2	2,0	8,9	1,5

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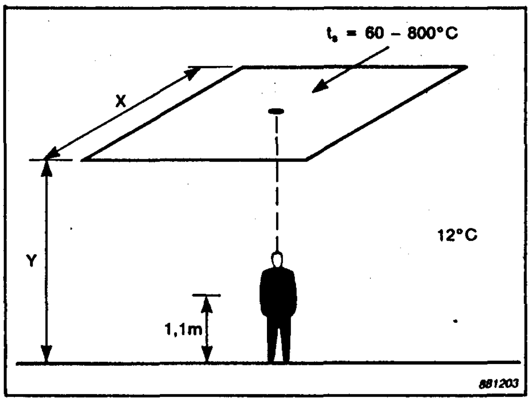

Fig. 4. A rectangular radiant source positioned above the head of a person, used for comparing different methods of estimating the mean radiant temperature

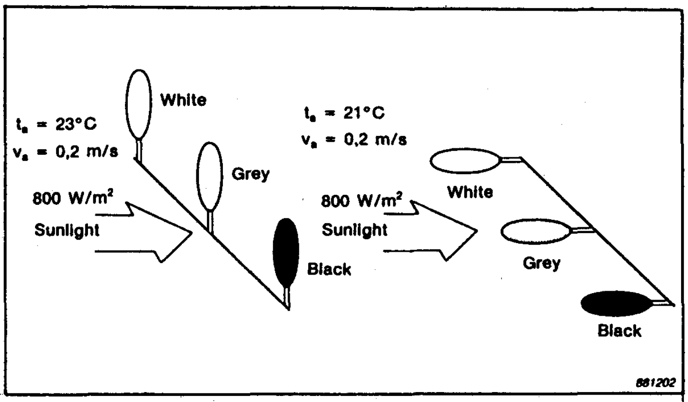

Fig. 5. Test set-up for starting the influence of the colour of the sensor when exposed to sunlight

Table 3. Results of the influence of colour and direction of a sensor, when exposed to sunlight

	Sunlight intensity W/m²	Air temp. °C	Air velocity m/s	Operative Temperature white °C	grey °C	black °C
Sunlight on the top	800	21	0,2	25	30	35
Sunlight on the side	800	23	0,2	31	44	58

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The sun has, as expected, the smallest influence on the white sensor and the highest influence on a black sensor. The sun-radiation coming from the top of the sensor (simulating the sun above the head of a standing person) the operative temperature increased in relation to the white, with 5°C for the grey, and 10°C for the black sensor. This means that the mean radiant temperature has then increased by about double these values. For the sun coming from the side the effect is even greater due to the greater projected area in this direction. The effect of the direction is rather significant i.e. 14°C increase in operative temperature for the grey sensor. As the human skin/clothing in general will have radiant properties close to the grey, serious over-estimates of the influence of short wave radiation will be made by using a black sensor. If at the same time also the sensor has a sphere shape like a globe the over-estimation will be even greater.

OPERATIVE TEMPERATURE

Operative Temperature (t_o) is defined as the uniform temperature of an enclosure in which an occupant would exchange the same amount of heat by radiation plus convection as in the existing non-uniform environment;

The operative temperature was introduced by Gagge et al. [1937] and has been used ever since in the description of the indoor thermal environment. The exact equation for the operative temperature is:

$$t_o = \frac{h_c \cdot t_a + h_r \cdot \bar{t}_r}{h_c + h_r} \tag{3}$$

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

this may also be written as

$$t_o = a \cdot t_a + (1 - a) \cdot \bar{t}_r \qquad \text{where} \qquad a = h_c / (h_c + h_r) = 1 / (1 + h_r / h_c) \tag{4}$$

One requirement for a sensor for direct measurement of operative temperature is that the relation between the radiant- and convective heat loss coefficient is the same as for a person. Using the equation for the convective heat loss coefficient, h_c, given by Fanger [1982] it is possible to estimate the diameter of a sensor which will have the same relation h_c / h_r as for a person. This has been shown in Fig. 3. Here it is seen that the optimal diameter of a sensor is around 4–10 cm. A standard globe of 15 cm diameter will overestimate the influence of the mean radiant temperature.

Both the definition of the operative temperature and the equation (3), (4) 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 person. 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.

EQUIVALENT TEMPERATURE

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. The equivalent temperature is characterized by the fact that the dry heat loss from a person – thus the degree of thermal comfort – is the same 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:

$$t_{eq} = 0{,}522 \cdot t_a + 0{,}478 \cdot \bar{t}_r - 0{,}2 \cdot \sqrt{v_a} \cdot (37{,}8 - t_a)\,^\circ\mathrm{C} \tag{5}$$

Gagge [1940] introduced the standard operative temperature:

$$t_{so} = 0{,}48 \cdot \bar{t}_r + 0{,}52 \left[\sqrt{\frac{v_a}{0{,}076}} \cdot t_a - \left(\sqrt{\frac{v_a}{0{,}076}} - 1 \right) \cdot t_{cl} \right] {}^\circ\mathrm{C} \tag{6}$$

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:

$$t_{sub} = \frac{0{,}44 \cdot \bar{t}_r + 0{,}56 \cdot \left(5 - \sqrt{10 v_a} \cdot (5 - t_a)\right)}{0{,}44 + 0{,}56 \cdot 10 v_a}\,^\circ\mathrm{C} \qquad \text{for} \quad v_a \geqslant 0{,}15\ \mathrm{m/s} \tag{7}$$

$$t_{sub} = 0{,}56 \cdot t_a + 0{,}44 \cdot \bar{t}_r\,^\circ\mathrm{C} \qquad \text{for} \quad v_a < 0{,}15\ \mathrm{m/s}.$$

The equivalent temperature may be calculated by the PMV equation (Fanger [1982]) as the temperature (air temperature = mean radiant temperature) that gives the same degree of comfort (PMV value), with the air velocity equal to zero as the actual combination of air temperature, mean radiant temperature and air velocity.

Madsen [1979] has given an equation that includes the influence of the clothing insulation (I_{cl}):

$$t_{eq} = 0{,}55 \cdot t_a + 0{,}45 \cdot \bar{t}_r + \frac{0{,}24 - 0{,}75 \cdot \sqrt{v_a}}{1 + I_{cl}} (36{,}5 - t_a)\,°\mathrm{C} \tag{8}$$

where the last term is included when $v_a > 0{,}1$ m/s.

All these temperatures include the cooling effect of an air movement.

Fig. 6 shows how Bedford's, Gagge's, McIntyre's, and Madsen's expressions agree with the comfort equation. 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.

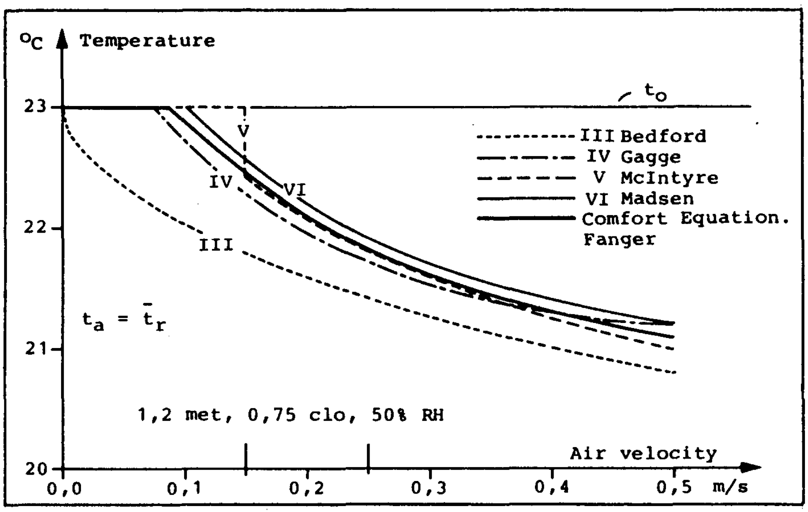

Fig. 6. The Dependence of the equivalent temperature on air velocity according the equations (3), (4) (5) and (7). Calculated equivalent temperatures are compared to an equivalent temperature calculated from Fanger's comfort equation $t_a = \bar{t}_r = t_o = 23°C$

The requirements to a sensor for direct measurements of equivalent temperature is that the size, colour and shape, fulfils the requirements for an operative temperature sensor and that the sensor is heated to a surface temperature, which simulates the mean clothing surface temperature of a person. From the definition it is seen that the equivalent temperature depends on the clothing insulation, which means that the sensor should be able to simulate different clothing temperatures.

These requirements are fulfilled with the sensor in Fig. 3. The sensor has been carefully designed to simulate the dry heat loss from a person as precisely as possible. 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. The form of the sensor gives approximately the same projected-area factor in the three main axes as does a person. 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. 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.

When measuring the equivalent temperature, the sensor is heated. 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. By means of the measured heat loss and mean surface temperature, the equivalent temperature is estimated.

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 (40 sec.) with the sensor smaller than the time constant for measuring the operative temperature with a globe (7,5 min). The time constant for the sensor when measuring operative temperature (2 min) is also smaller than for a normal globe made out of copper (Fig. 7) (Madsen [1979]).

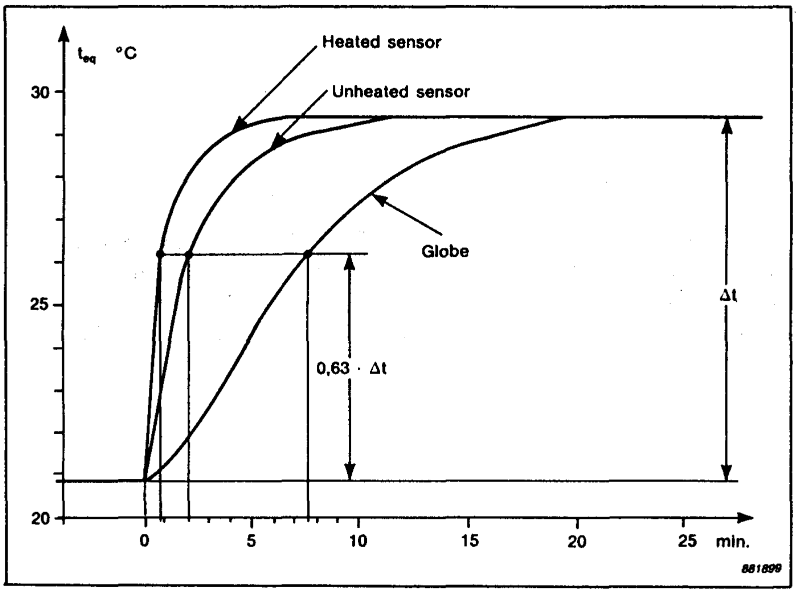

Fig. 7. Response time of a heated and an unheated comfort sensor together with a copper globe thermometer. The time constant is the time (Δt) when the measured value reaches 67% of the final value

DISCUSSION

The above sections have described the requirements and discussed different methods for measuring mean radiant, operative- and equivalent temperature.

All these temperature parameters are related to the dry heat loss i.e. convection and radiation from the human body. This represents in moderate thermal environments about 80% of the total heat loss. By measurement of air temperature, mean radiant temperature and air velocity both operative and equivalent temperature may be calculated. It is, however, often difficult to measure mean radiant temperature and air velocity very accurately. This means that also the precision on the estimated operative- or equivalent temperature is not very good, because the accuracies on air-, mean radiant temperature and air velocity adds up. Instead it is better to make an integrated value in the form of operative- or equivalent temperature. As seen from the previous sections it does not alone depend on the accuracy of the temperature measurements as such; but more significant in many cases is the shape, size and colour of the sensor. In well insulated buildings, where the difference between air and mean radiant temperatures are relatively small, the size of the sensor is not that important. If the radiant sources (heating systems, windows) are uniformly distributed the shape of the sensor will have a less significant influence on the measured operative- or equivalent temperature. If there, however, is concentrated radiant sources, direct sunshine or significant differences between air- and mean radiant temperature it will be very important to optimize the size (5–10 cm), colour (pink, light grey) and shape of the sensor.

Olesen et al. [1987] has shown how the measurement of operative- and equivalent temperature combined with an air temperature measurement can be used to estimate the mean radiant temperature and the air velocity.

That the operative temperature does not respond to air velocity is clearly demonstrated in Fig. 6. The increased air velocity upto 0,5 m/s will reduce the temperature felt by a person from 23°C to 21°C, while the operative temperature is constant because air- and mean radiant temperature is equal.

CONCLUSION

In the present paper different methods for estimating/measuring the mean radiant temperature and operative temperature has been compared (weighted mean value of the plane radiant temperature in six directions, a sphere shaped globe sensor, a ellipsoide shape "globe" sensor).

The comparison showed that for a space with evenly distributed radiant sources (office, schools, industry) the difference between the methods are small.

For concentrated high temperature radiant sources above the head of a person there is a difference between the methods. A sphere shaped sensor (globe thermometer) will significantly over-estimate the influence of the overhead radiation compared to a person. Using an ellipsoide shaped sensor or the plane radiant temperature in six directions give a much better approximation.

When measuring the influence of sunlight on a person both the colour (white, grey, black) of the sensor and the direction of the sun has a significant influence. The optimal size of a sensor for measuring the operative temperature in moderate thermal environments is 5–10 cm.

When measuring equivalent temperature the sensor must fulfil the same requirements as for measuring operative temperature and in addition be heated to simulate the surface temperature of a clothed person.

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