THERMAL ENVIRONMENTAL PARAMETERS AND THEIR MEASUREMENT

Th L Madsen
Technical University of Denmark, Copenhagen

It is a well known fact that the following six physical parameters influence man's thermal comfort: air temperature, humidity, air velocity and mean radiant temperature determined by the environment, and activity level and clothing determined by the individual.

The interrelation of these parameters is given by a so-called thermal comfort equation. The most complete equation has recently been set up by Fanger who has also defined a new index for thermal comfort which has been named the PMV-index (predicted mean vote) (P.O. Fanger: Thermal Comfort, *Copenhagen 1970). In the paper the relative influence of the various parameters on thermal comfort is discussed. Also it is briefly described how the PMV-value can be computed from the thermal comfort equation when the environmental parameters are known. It is however difficult to measure the various parameters with sufficient accuracy using commercially available instruments, therefore a new instrument has been developed, which measures the total heat loss to the environment corresponding to the heat loss from a person in thermal comfort. The signal from the sensing body is fed into a simple resistance network which performs the necessary calculations so that the PMV-value can be read directly on the instrument scale. The activity level and insulation value of the clothing can be set on the instrument.*

Introduction

The purpose of indoor thermal measurements is to determine the degree of thermal comfort for those persons who are to occupy the particular locality. In order to be able to evaluate the thermal climate in a room, a knowledge of the following six parameters is necessary:

For the person:	activity level q
	clothing m
For the room:	air temperature t_a
	mean radiant temperature t_{mrt}
	air velocity v
	partial water vapour pressure of the air p_a

Over the years numerous thermal comfort indexes have been formulated containing a greater or lesser number of these parameters, but it was in 1970, with P.O. Fanger's PMV-index (Predicted Mean Vote-index)[1], that a thermal comfort index first became available which took all six climate parameters into consideration.

The index is based on a modified version of the generally applied ASHRAE scale, i.e.

cold	given the numerical value				-3
cool	"	"	"	"	-2
slightly cool	"	"	"	"	-1
neutral	"	"	"	"	0
slightly warm	"	"	"	"	+1
warm	"	"	"	"	+2
hot	"	"	"	"	+3

It is well known that the organism is capable of maintaining a heat balance even when the ambient temperature varies within wide limits. Within a relatively narrow zone including the comfort zone the heat balance is maintained by vasomotor action, and under greater thermal loads, by sweating or shivering.

It is reasonable to presume, therefore, that the degree of thermal discomfort is closely related to the thermal load which the environment impresses on the person, and consequently the degree of thermal discomfort can be expected to be a function of the thermal load.

Fanger has defined the degree of thermal discomfort (the PMV-value) at a given activity level as a function of the difference between the internal heat production (metabolism) and the heat loss to the actual environment from a person with skin temperature and sweat production corresponding to thermal comfort at the actual activity level.

It is now possible to calculate the PMV-value for all combinations of the above-mentioned six thermal climate factors. However, the expression for the calculation of the PMV-value is so complicated that it is suitable only for computer calculation. In Fanger[1] the PMV-value is calculated and given in tabular form for six activity levels, seven clo-values, nine air velocities, one relative air humidity and eight temperatures, the air temperature and the mean radiant temperature assumed to be the same.

In order to obtain a clearer expression of the degree of thermal discomfort, Fanger has derived another thermal index called PPD (Predicted Percentage Dissatisfied). The PPD-index is based on investigations performed with approx. 1300 American and Danish subjects. A comparison was drawn between the calculated PMV-value at each experiment and the percentage of the subject who, in the same experiment, voted for -3, -2, +2 or +3, i.e. those who have been decidedly thermally dissatisfied. This comparison resulted in Fig. 1, which gives directly the connection between the PMV- and PPD-indexes.

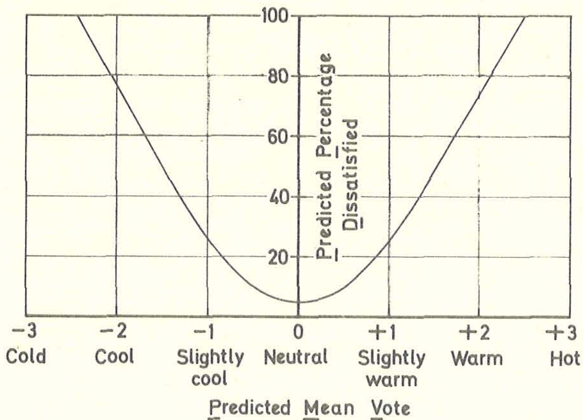

Figure 1. *Predicted Percentage Dissatisfied (PPD) as a function of Predicted Mean Vote (PMV).*

It appears that in a largish group of persons, exposed at the same activity level and clothing to the same thermal environment, it is impossible to satisfy everyone thermally. Even when the group as a whole votes neutral, 0 on the PMV-scale, 2.5% of the group will vote for -2 or -3 and a corresponding 2.5% will vote for +2 or +3.

In this paper the PMV-index will be used to assess the degree of accuracy necessary in order to measure the individual climate parameters; it will also be used as a basis for the construction of an instrument for the direct determination of the PMV-value on the basis of a measurement of the dry heat loss to the environment from a sensor with the same surface temperature, emissivity, angle factors and orientation as the clothed person whose PMV-value is to be determined.

Measuring the thermal climate parameters of the environment

The air temperature, together with the air velocity, determines the convective heat exchange (q_c) between person and environment. In Fig. 2, q_c can be seen as a function of v at various temperature differences between person and air. t_a can be measured with almost all types of thermometers. Those usually used are liquid thermometers, thermo elements or electrical resistance thermometers. They all have one thing in common, i.e. they measure a temperature which lies between t_a and t_{mrt}. The smaller the sensor, and the lower the emissivity of its surface, the closer it comes to t_a. The most accurate and at the same time the quickest measurements are obtained when a strong enforced convection is created around the sensor, e.g. by sucking air through a chromium-plated tube in which the thermo sensor is placed.

The air velocity is usually determined either by measuring the heat loss from a sensor, when a constant temperature difference exists between sensor and t_a, or by measuring this temperature difference on a sensor with constant heat supply. The sensor consists of a small globe or, more often, of a thin wire. The globe is most suitable because it measures omnidirectionally and because its greater time constant contributes to a levelling out of the quickest velocity changes. v will nearly always be irregular in speed and direction. Therefore it is necessary to determine the average over a few minutes; this can be done either by registering v on a recorder or by using a sensor with a high time constant.

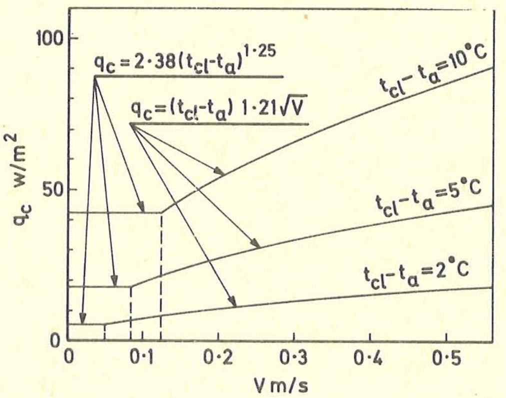

Figure 2. *The convective heat loss (q_c) from a person as a function of the air velocity (v) at various temperature differences between person and air.*

From Fig. 2 it will be seen that a certain air velocity is necessary in order to break the boundary layer created by the thermal buoyancy around a heated body. This is why many thermal anemometers are unsuitable for measuring v in the low velocity zone 0 – 0.5 m/s, which normally occurs in occupied zones. The high temperature – often greater than 100°C – causes the self convection to be disturbing in velocity measuring at low speeds. In addition, the measured velocity will be dependent upon its direction. A downward air stream will hinder the self convection and consequently the measured velocity will be too low, while an upward air stream will promote the self convection so that the measured velocity will be too great. Investigations made by the "Statens Institut för Byggnadsforskning"[2] and K.T.H.[3] in Sweden seem to show that the practical measuring inaccuracy when using hot-wire anemometers in the area 0.2 – 2.5 m/s is ±35%. For $v < 0.2$ m/s the percentage is higher. On one anemometer, Wad[4], the sensor is ingeniously designed to compensate for this condition. By allowing the hot-wire to vibrate so that it constantly tends to swing out of its own convection field, one is able to measure velocities of between -0.3 and +0.3 m/s in both speed and direction, with an uncertainty of ±0.01 m/s.

The mean radiant temperature can be defined as that uniform temperature of absolutely black surroundings which will give the same heat exchange by radiation between person and surroundings as the actual (non-uniform) surroundings under consideration. As this definition implies, t_{mrt} must be given in relation to a certain object, as a rule a person with a given position and orientation in the room. Thus, the same surroundings need not necessarily have the same t_{mrt} for a standing and a seated person. A correct determination of t_{mrt} can therefore be made only in the following two ways, each differing in principle.

1. By measuring the temperature of the surrounding surfaces and then calculating the heat exchange by radiation between these and the person whose t_{mrt} is to be determined. In Fanger[1] the angle factors and the radiation areas, etc. are given for both standing and seated persons in typical rooms.

2. By measuring the heat exchange by radiation between the actual surroundings and a sensor having a shape, surface temperature, emissivity, orientation and placement the same as that for the person whose t_{mrt} is to be determined.

Method 1 is both difficult and time-consuming to perform and no instruments are available which fulfil the requirements for Method 2, although over the years numerous instruments have been devised for measuring t_{mrt}, usually in relation to a globe. In Fanger[1] alone, 13 are mentioned, all with one thing in common – only prototypes exist and they therefore cannot be purchased. Usually one ends up measuring t_{mrt} with a globe thermometer, the only good property of which is that it is inexpensive and simple. Among its inferior qualities is that besides the measured globe temperature, a knowledge of both t_a and v is necessary before t_{mrt} can be calculated; moreover, t_{mrt} is determined in relation to a globe which is a reasonable geometrical approximation of only a few people.

One can conclude, therefore, that t_{mrt} in most cases is determined with rather much inaccuracy, even though at small velocities it has almost the same influence on the degree of thermal comfort as t_a.

The influence of the *air humidity* on the degree of thermal comfort is so slight in and near the comfort zone, that its determination rarely causes any difficulties. The water vapour pressure will normally be the same over the whole room, so that measuring at a single point will be sufficient. All types of instrument for the measuring of relative humidity, dew point or water vapour pressure can be used, as long as they are in good condition and carefully calibrated.

Assessment of the necessary and sufficient measuring accuracy

The PMV- and PPD-indexes are good tools for determining how accurate it is necessary and sufficient to measure the individual thermal climate parameters when it is desired to know the degree of thermal discomfort at a given accuracy.

A. When the desired accuracy of the PMV- or PPD-value is given, the necessary measuring accuracy of the individual climate parameters can be calculated.

B. If, on the other hand, the measuring uncertainty in the determination of the individual climate parameters is known, the uncertainty of the PMV- or PPD-value found on the basis of these measurements, can be calculated.

Fanger's expression for the determination of the PMV-value can be expressed as:

$$PMV = f(q, m, t_a, t_{mrt}, v. p_a)$$

As the activity level (q) and the clothing (m) are not usually included in the actual measuring, the 'indefiniteness' of the PMV-value can, according to the classic measuring theory, be found by the expression:

$$u_{PMV} = \sqrt{\left(\frac{\partial PMV}{\partial t_a} . u_{t_a}\right)^2 + \left(\frac{\partial PMV}{\partial t_{mrt}} . u_{t_{mrt}}\right)^2 + \left(\frac{\partial PMV}{\partial v} .u_v\right)^2 + \left(\frac{\partial PMV}{\partial p_a} .u_{p_a}\right)^2}$$

where u_{t_a}, $u_{t_{mrt}}$, u_v and u_{p_a} are the 'indefiniteness' of the individual climate parameters. Thus they are determined partly by the measuring equipment available, and partly by the number of measurements which form the basis for the calculation of the PMV-value.

$$\frac{\partial PMV}{\partial t_a}, \frac{\partial PMV}{\partial t_{mrt}}, \frac{\partial PMV}{\partial v} \text{ and } \frac{\partial PMV}{\partial p_a}$$

is calculated for several values of q, m and v, and the results of these calculations are shown in Tables 1-4.

TABLE 1. $\frac{\partial PMV}{\partial t_a}$ (PMV/°C) as a function of activity level, clothing and air velocity.

q W/m²	m clo	v m/s 0.1	0.2	0.5	1.0	2.0
	0	0.28	0.37	0.59	0.82	1.13
	0.5	0.20	0.23	0.32	0.38	0.46
60	1.0	0.14	0.17	0.22	0.26	0.29
	1.5	0.12	0.14	0.17	0.20	0.22
	2.0	0.09	0.11	0.13	0.15	0.18
	0	0.14	0.19	0.29	0.41	0.57
	0.5	0.09	0.11	0.16	0.20	0.23
120	1.0	0.07	0.08	0.11	0.13	0.14
	1.5	0.06	0.06	0.08	0.10	0.11
	2.0	0.05	0.05	0.06	0.08	0.08
	0	0.13	0.16	0.25	0.35	0.50
	0.5	0.08	0.10	0.14	0.17	0.20
180	1.0	0.06	0.07	0.09	0.12	0.13
	1.5	0.05	0.06	0.07	0.09	0.09
	2.0	0.04	0.05	0.06	0.07	0.08

TABLE 2. $\frac{\partial PMV}{\partial t_{mrt}}$ (PMV/°C) as a function of activity level, clothing and air velocity.

q W/m²	m clo	v m/s 0.1	0.2	0.5	1.0	2.0
	0	0.28	0.28	0.29	0.29	0.30
	0.5	0.19	0.17	0.15	0.13	0.11
60	1.0	0.13	0.12	0.10	0.09	0.07
	1.5	0.10	0.09	0.07	0.06	0.05
	2.0	0.08	0.07	0.06	0.05	0.04
	0	0.14	0.14	0.15	0.15	0.15
	0.5	0.08	0.09	0.07	0.07	0.06
120	1.0	0.06	0.06	0.05	0.04	0.03
	1.5	0.04	0.04	0.03	0.03	0.02
	2.0	0.03	0.03	0.03	0.02	0.02
	0	0.11	0.12	0.12	0.12	0.12
	0.5	0.06	0.07	0.06	0.05	0.05
180	1.0	0.05	0.05	0.04	0.03	0.03
	1.5	0.03	0.03	0.03	0.02	0.02
	2.0	0.03	0.03	0.02	0.02	0.01

TABLE 3 $\frac{\partial PMV}{\partial v}$ (PMV/m/s) as a function of activity level, clothing and air velocity.

q W/m²	m clo	v m/s 0.1	0.2	0.5	1.0	2.0
	0	-7.31	-4.29	-2.11	-1.22	-1.30
	0.5	-4.80	-2.40	-1.03	-0.51	-0.46
60	1.0	-3.19	-1.65	-0.67	-0.31	-0.25
	1.5	-2.49	-1.27	-0.48	-0.23	-0.19
	2.0	-1.85	-0.95	-0.36	-0.18	-0.15
	0	-5.26	-3.20	-1.58	-0.90	-0.94
	0.5	-3.15	-1.85	-0.74	-0.36	-0.32
120	1.0	-2.37	-1.18	-0.45	-0.22	-0.17
	1.5	-1.82	-0.96	-0.35	-0.16	-0.13
	2.0	-1.30	-0.70	-0.27	-0.12	-0.09
	0	-6.12	-3.78	-1.85	-1.03	-1.05
	0.5	-3.60	-2.13	-0.90	-0.42	-0.38
180	1.0	-2.59	-1.43	-0.55	-0.27	-0.22
	1.5	-1.86	-1.04	-0.40	-0.19	-0.15
	2.0	-1.60	-0.90	-0.31	-0.15	-0.13

TABLE 4 $\frac{\partial PMV}{\partial p_a}$ (PMV/mbar) as a function of activity level, clothing and air velocity.

q W/m²	m clo	v m/s 0.1	0.2	0.5	1.0	2.0
	0					
	0.5					
60	1.0			0.029 (all velocities)		
	1.5					
	2.0					
	0					
	0.5					
120	1.0			0.017 (all velocities)		
	1.5					
	2.0					
	0					
	0.5					
180	1.0			0.018 (all velocities)		
	1.5					
	2.0					

In Tables 5 and 6, $\frac{\partial PMV}{\partial q}$ and $\frac{\partial PMV}{\partial m}$ are indicated for various values of q and m. Thus also the importance of the uncertainty of the estimation of the activity level and the clothing can be taken into consideration in the calculation of the PMV-value's 'indefiniteness.'

TABLE 5. $\frac{\partial PMV}{\partial q}$ (PMV/W/m^2) as a function of activity level, clothing and air velocity.

q	m	v m/s				
W/m^2	clo	0.1	0.2	0.5	1.0	2.0
	0	0.054	0.056	0.065	0.067	0.078
	0.5	0.044	0.047	0.050	0.052	0.055
60	1.0	0.041	0.043	0.045	0.047	0.048
	1.5	0.038	0.040	0.041	0.042	0.043
	2.0	0.037	0.038	0.039	0.040	0.041
	0	0.028	0.031	0.033	0.037	0.043
	0.5	0.024	0.025	0.027	0.027	0.028
120	1.0	0.022	0.023	0.024	0.024	0.024
	1.5	0.021	0.021	0.022	0.022	0.022
	2.0	0.021	0.021	0.021	0.021	0.021
	0	0.024	0.025	0.029	0.032	0.036
	0.5	0.021	0.022	0.023	0.023	0.024
180	1.0	0.019	0.019	0.020	0.020	0.021
	1.5	0.018	0.018	0.018	0.018	0.019
	2.0	0.017	0.017	0.017	0.017	0.018

TABLE 6. $\frac{\partial PMV}{\partial m}$ (PMV/clo) as a function of activity level, clothing and air velocity.

q	m	v m/s				
W/m^2	clo	0.1	0.2	0.5	1.0	2.0
	0	3.20	3.60	5.00	5.90	7.80
	0.5	2.00	2.24	2.76	3.04	3.34
60	1.0	1.40	1.54	1.74	1.90	2.04
	1.5	1.10	1.18	1.28	1.36	1.44
	2.0	0.96	1.00	1.10	1.14	1.18
	0	2.42	3.14	4.00	5.20	6.50
	0.5	1.62	1.86	2.18	2.58	2.84
120	1.0	1.18	1.30	1.44	1.56	1.68
	1.5	0.90	0.96	1.04	1.13	1.18
	2.0	0.71	0.75	0.80	0.85	0.90
	0	2.90	3.80	4.66	6.60	7.40
	0.5	1.92	2.20	2.50	2.90	3.33
180	1.0	1.40	1.52	1.70	1.90	2.05
	1.5	1.06	1.12	1.22	1.34	1.40
	2.0	0.82	0.85	0.90	1.00	1.10

Examples of A *and* B

A. In office accommodation, the occupants of which are considered to have an activity level of 60 kcal/h m^2 and a clothing of 0.5 clo, it is desired to determine the thermal condition so that the percentage thermally dissatisfied will be less than 7.

From Fig. 1 it can be seen that the permissible 'indefiniteness' of the PMV-value will be ±0.3 PMV.

Normally one aims at an equal distribution of the contribution of each factor to the combined 'indefiniteness' in the result. This consideration will involve the following connection between the measuring accuracy of the four climate parameters:

$$\frac{\partial PMV}{\partial t_a} . u_{t_a} = \frac{\partial PMV}{\partial t_{mrt}} . u_{t_{mrt}} = \frac{\partial PMV}{\partial v} . u_v = \frac{\partial PMV}{\partial p_a} . u_{p_a} = a$$

and thus $u_{PMV} = \sqrt{4a^2} = 2a = \pm 0.3$ PMV

or $a = \pm 0.15$ PMV

By means of Tables 1-4 we then obtain (presuming v to be $\leqslant 0.1$ m/s):

$$u_{t_a} = \frac{\pm 0.15}{0.20} = \pm 0.75^oC$$

$$u_{t_{mrt}} = \frac{\pm 0.15}{0.19} = \pm 0.80^oC$$

$$u_v = \frac{\pm 0.15}{4.8} = \pm 0.03 \text{ m/s}$$

$$u_{p_a} = \frac{\pm 0.15}{0.029} \quad \pm 5 \text{ mbar}$$

It can be seen that it will be easy to obtain the necessary measuring accuracy for t_a and p_a, while the practical measuring accuracy as regards t_{mrt} and v is barely acceptable.

B. In the same case, let us suppose that the PMV-value is calculated on the basis of measurements made with the following measuring uncertainties:

$u_{t_a} = \pm 0.2^oC$

$u_{t_{mrt}} = \pm 1.0^oC$

$u_v = \pm 0.1$ m/s

$u_{p_a} = 2$ mbar

$$u_{PMV_1} = \sqrt{(0.20 \times 0.2)^2 + (0.19 \times 1)^2 + (4.8 \times 0.1)^2 + (0.029 \times 2)^2}$$

$$= \sqrt{0.0016 + 0.0361 + 0.2304 + 0.0034} = \sqrt{0.2715}$$

$= \underline{0.52 \text{ PMV}}$ of which the 0.48 is due to u_v.

If it is further presumed that the uncertainty of the establishment of q and m is:

$$u_q = \pm 10 \text{ W/m}^2$$

$$u_m = \pm 0.1 \text{ clo}$$

we obtain $u_{PMV_2} = \sqrt{0.2715 + (0.044 \times 10)^2 + (2.00 \times 0.1)^2}$

$$= \sqrt{0.2715 + 0.1936 + 0.0400} = \sqrt{0.5051}$$

$$= \underline{\underline{\pm 0.71 \text{ PMV}}}$$

Presuming that the four climate parameters of the environment could be measured without uncertainty, there would nevertheless, due to the difficulty of establishing the activity level and the clothing, be the following uncertainty in the calculated PMV-value:

$$u_{PMV_3} = \sqrt{0.1936 + 0.0400} = \sqrt{0.2336} = \underline{\underline{\pm 0.48 \text{ PMV}}}$$

In any measurements in practice it will hardly be realistic to calculate with uncertainties less than those given for q and m. In tables of typical activity levels these are nearly always given with 0 as the last digit, whereas m in the corresponding tables for clo-values is usually given with one decimal. Added to this, there is the practical spreading of both quantities to different persons in the same room.

An instrument for the direct measuring of PMV- and PPD-values

The purpose of measuring the thermal climate parameters of the environment is to be able to determine the heat loss to this environment from a person with a given activity level and clothing. However, it seems illogical to take on all the problems associated with the technique of measuring which an individual determination involves, when afterwards the individual parameters must anyway be set up in a complicated formula before their combined thermal influence on a person can be ascertained. It is considerably quicker, simpler and more accurate to determine the joint effect of t_a, t_{mrt} and v on a person by measuring the heat loss q_F from an analogous sensor. In other words, a sensor with the same surface temperature, emissivity, angle factors, orientation and placement as the person it is meant to simulate.

Moreover, it appears that the PMV-value can be calculated on a simple resistance network, when q_F, q, m and p_a are known. The ideal instrument thus takes the form of a sensor for measuring q_F, a regulating circuit for the control of the sensor's surface temperature dependent on the clothing (clo-value) set on the instrument, a resistance network on which besides the clothing, the activity level (W/m^2) and the water vapour pressure (mbar) can be set, and lastly, a meter to indicate the desired PMV- and PPD-values.

The sensing body (Fig. 3)

The purpose of this part of the apparatus is to determine the dry heat emittance from a person to the actual surroundings, the person wearing the clothing set on the instrument. This is achieved by an appropriate choice of the sensor's:

size
shape
orientation
radiation properties
surface temperature

The *size* is chosen so that the relationship between the heat emittance by convection and by radiation is the same as for a person. According to Fanger[1], the effective radiant area of a person is only 0.7 times as great as the convection area. This is due to the fact that a reciprocal radiation exchange occurs between some parts of the body, e.g. between the inner sides of the legs and between the arms and the sides of

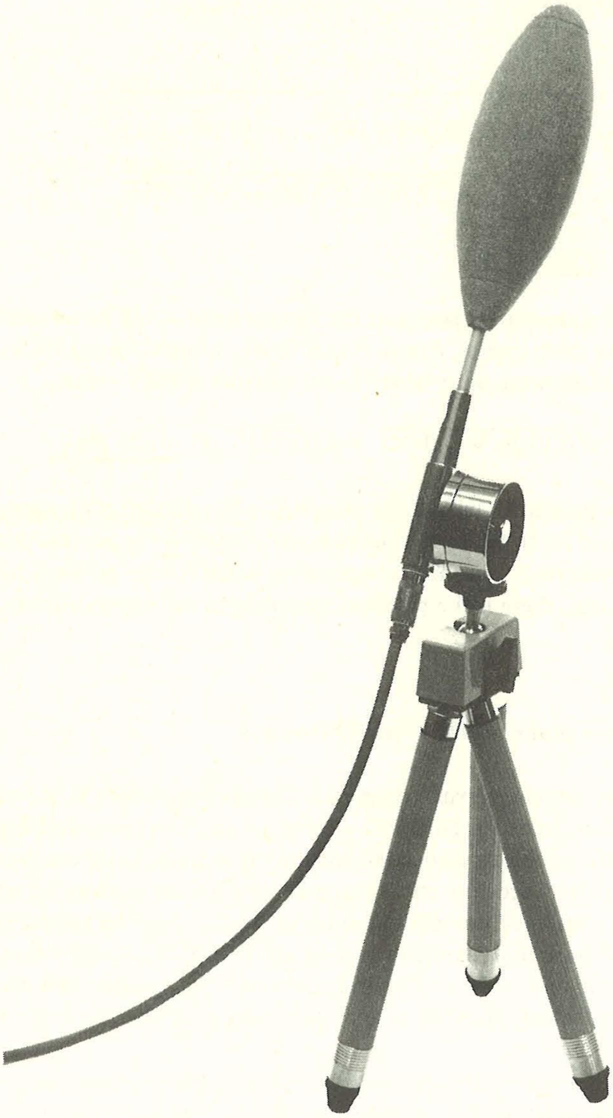

Figure 3. *The sensing body.*

the body. On the other hand, the sensor's radiation- and convection-areas are equal. This means that the sensor will emit $\frac{1}{0.7}$ = 1.4 times as much heat per area unit during radiation as a person would at the same spot. However, it is propitious that a heated body's convective heat emittance per area unit becomes greater when the body becomes smaller. Therefore the main dimensions of the sensor are chosen so that its convective heat emittance per area unit is $\frac{1}{0.7}$ = 1.4 times as great as for a person. In other words, the sensor emits, at the same surface temperature, 1.4 times as much heat per area unit to the environment as a person would emit.

The *shape* of the sensor is the result of the efforts to obtain the same projected radiation area factors for the sensor as for a person in the six main directions. The sensor should therefore have been a double ellipsoid, but the ratio between right/left and forward/backward is, according to Fanger[1], 0.23 : 0.35, which has been insufficient to justify the technological problems by a double ellipsoid. On the other hand, the ratio up/down deviates so much from those mentioned – for a standing person 0.08 – that it provides good grounds for a special design, especially with regard to those air-conditioning plants where the ceiling constitutes an active part (heating- and cooling-ceilings). Moreover, lighting is often of such a quantity that it is desirable to take proper account of its heat radiation.

The result of these considerations is a rotating ellipsoid, with the greatest radiation area relationship (0.28) at right angles to the rotation axis, and the smallest (0.08) parallel to the rotation axis.

The *orientation* can be chosen as I, II or III by setting the cylindrical connecting link between the sensor and the tripod, corresponding respectively to a standing, seated or recumbent person. Thus the sensor's area relationship in the main directions of the room will be in agreement with that of a person in the same position.

The *radiation properties* are chosen so that for long-wave radiation it corresponds to the absorptance for both a nude and a clothed person. For short-wave radiation (solar) the absorptance depends on the colour of the surface. One cannot simulate persons in both light and dark clothing with a single sensor. The colour of the sensor is chosen so that it corresponds to uncovered skin and rather light clothing.

The *surface temperature.* By means of the measuring instrument's adjusting knob for clothing, the regulating system for controlling the surface temperature of the sensor can be varied, so that after a short period of adjustment (approx. 1 min) it assumes the same value as the mean surface temperature of a person in thermal comfort, with clothing corresponding to that set on the instrument. It is important that the sensor has the same mean surface temperature as the person it is meant to simulate, i.e., a person with clothing of the same clo-value as that set on the instrument, and with heat loss corresponding to thermal comfort in the actual surroundings. In this case the effect conveyed to the sensor (W/m^2) becomes a direct measure for the person's dry heat loss to the environment.

The *control circuit* for regulating the sensor's surface temperature. This consists of a Wheatstone measuring bridge, one branch of which is a nickel wire wound up around the sensor device. The bridge is adjusted so that it is in balance when the sensor's surface temperature is equal to the inner body temperature, corresponding to a heat loss of nil. The bridge controls the electrical effect conveyed to the sensor so that this becomes proportional to the imbalance of the bridge, i.e., to the difference between the body's inner temperature and its surface temperature. However, as the relationship between the temperature difference and the emitted effect depends on the clothing

$$t_{inner} - t_{surface} = q_{dry} \times (m_{skin} + m_{clothing})$$

the regulating circuit is arranged so that the proportionality factor ($m_{skin} + m_{clothing}$) alters when the clo-value is set on the instrument.

The *calculating device* (Fig. 4) for working out the PMV-value on the basis of the set values of activity level, clothing and water vapour pressure as well as the measured heat loss from the sensor. Figure 5 shows the relationship between the total and the dry heat loss from a person in the comfort zone, depending on the partial water vapour pressure of the air. It appears from this that it is possible to determine the total heat loss when the dry heat loss as well as the water vapour pressure are known. With the aid of the set water vapour pressure at (C), and the dry heat loss (measured by the sensor) from a person with clothing according to that set at (B), it is thus possible to determine the total heat loss (the activity level) for a person in thermal comfort in the actual surroundings. If this is equal to the activity set at (A), the PMV-value = 0. If the two activities differ, the calculating device will automatically calculate the PMV-value corresponding to this difference.

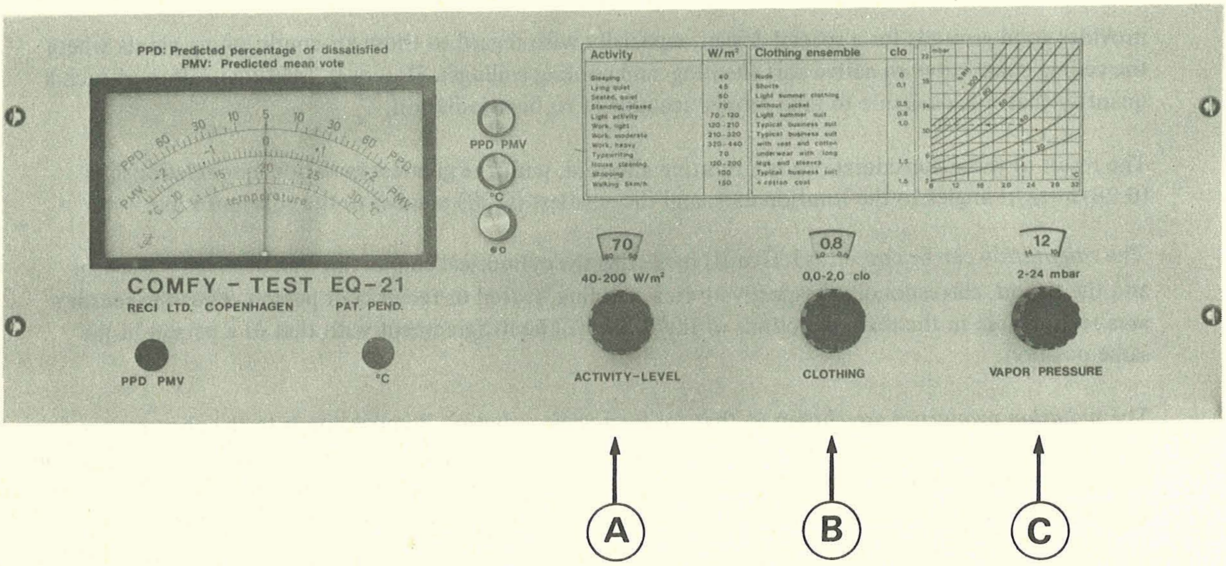

Figure 4. *The calculating unit and the measuring instrument.*

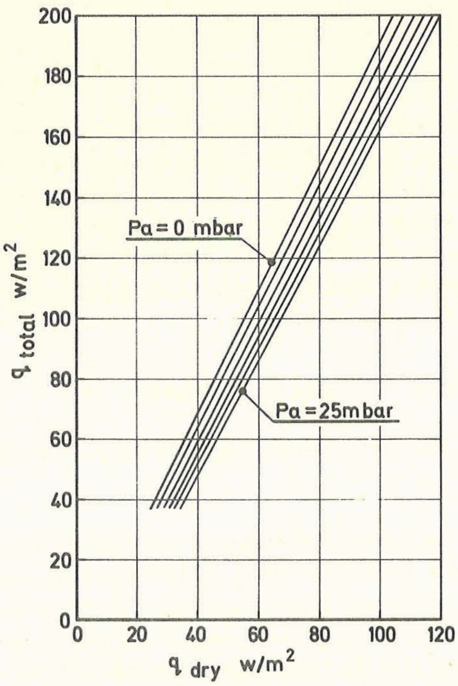

Figure 5. *The total heat loss from a person as a function of the dry heat loss and the water vapour pressure in the air.*

Measuring room temperature

As a consequence of the fact that most people still connect the term thermal comfort with temperature perception, the instrument is designed so that it can be used also for the determination of room temperature. *By room temperature is understood the equal value of mean radiant temperature and air temperature at air velocity nil, which gives the same dry heat loss from a person as the actual combination of mean radiant temperature, air temperature and air velocity.*

For both the person and the sensor, the following expression applies:

$$t_{inner} - t_{room} = q(m_{skin} + m_{clothing} + m_{environment})$$

Here t_{inner}, m_{skin} and $m_{environ.v=0}$ are known, $m_{clothing}$ can be chosen, after which t_{room} can be found as a function of q.

It is now a matter of choosing $m_{clothing}$ so that a suitable measuring interval is obtained for t_{room}. As the meter measures the voltage differences, which are proportional to the difference between q set on the instrument and q measured on the sensor, it will be practical to choose the set values of q and $m_{clothing}$ so that the two q's are equal (PMV = 0) for t_{room} = 20°C, and also so that a difference between the two q's corresponding to a pointer deflection of respectively +1 and -1 PMV, corresponds to a t_{room} of 25° and 15°C respectively. This gives a measuring zone for t_{room} of from +7.5 to +32.5°C.

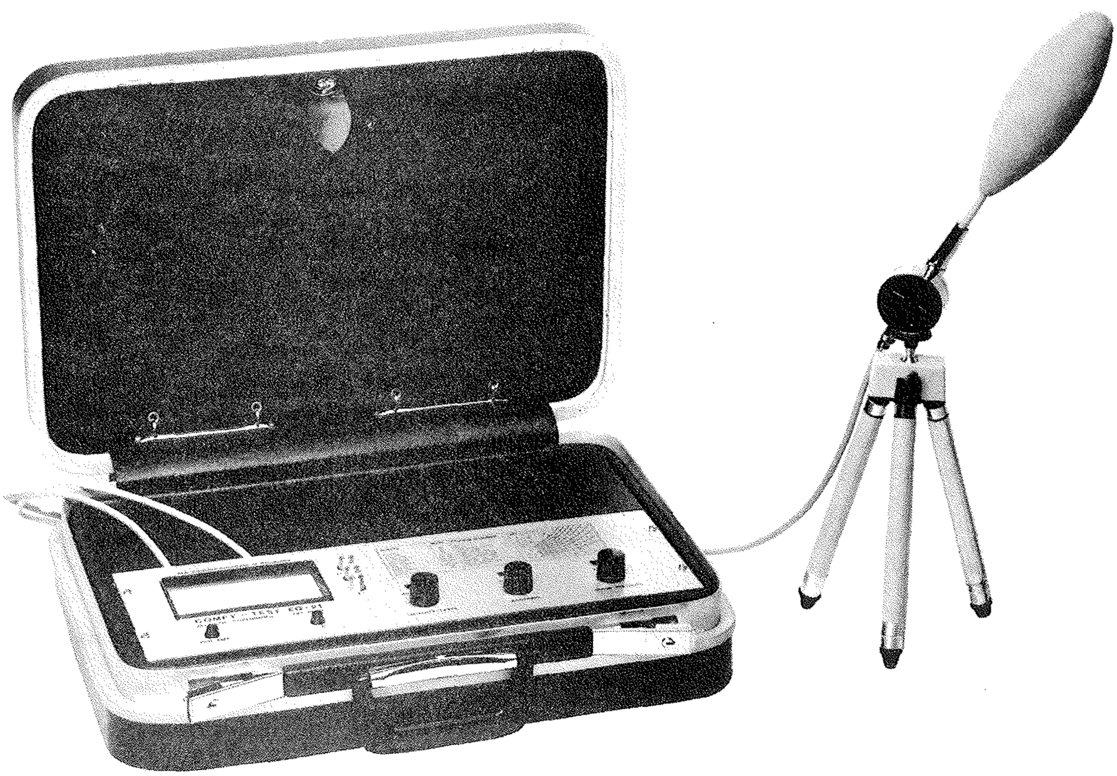

Figure 6. *The thermal comfort meter.*
(Comfy test manufactured by RECI LTD, Copenhagen).

The *measuring instrument* is a voltmeter with zero point in the middle of the scale, corresponding to PMV = 0 and t_{room} = 20°C and full deflection for plus or minus 1.0 volt, corresponding respectively to +2.5 PMV and t_{room} = 32.5°C or -2.5 PMV and +7.5°C. The instrument measures the difference between two voltages which are proportional to the set and the measured q_{dry} respectively. If, for example, the measured q_{dry} is greater than the set q_{dry}, this means that the environment is cooler than expected, i.e., that the PMV-value will be negative, or if the room temperature is measured, that this will be less than 20°C.

In addition to the two scales mentioned, a third scale can be found on the meter, the PPD-scale. This gives the percentage thermally dissatisfied persons to be expected at the values of activity level, clothing and water vapour pressure set on the instrument. The PPD-scale is based on Fig. 1.

References

1. **Fanger, P.O.** *Thermal Comfort,* Danish Technical Press, Copenhagen 1970.

2. **Svensson, Anders.** Instrument för mätning av lufthastigheter, *Swedish V.V.S. No. 1,* 1972, P. 23-28.

3. **Malmström, Tor-Göran and Neldet Ünal.** Riktingsberoende på grund av egenkonvektion hos varmtrådsanemometrar, *Swedish V:V.S. No. 9,* 1971, pp 56-58.

4. **Wad, Gustav.** The Low Velocity Anemometer, *DISA Information No. 7,* 1969, pp 32-35.

DISCUSSION

Prof. K. Ibamoto: In this kind of a study I feel it is necessary to measure both heat flow and surface temperature. Was the rate of heat supply kept at a constant level when you measured the change of surface temperature?

Mr. Madsen: No, this reaches its own equilibrium. You set the clo value corresponding to that required, and the surface temperature of the sensor will then equal the surface temperature of a man clothed in the clo value. You then measure the heat loss from the measuring body. If the measured heat flow is equal to the 'set activity level' then you have a PMV equal to zero. If they differ you will have a measure of the discomfort.

Mr. J.F. Nicol: You say it is reasonable to assume that the degree of thermal discomfort is related to the thermal load of the environment. There are other criteria to which it could be related. For example, a degree of vaso-constriction or dilation required to maintain thermal equilibrium. It makes a difference to the PMV which method is used.

Dr. P.O. Fanger: We thought that it was reasonable to take the heat load. What is needed is an index expressed in terms of environmental factors.

Mr. Nicol: The degree of vaso-regulation is a physiological measure, and more likely to be correlated with discomfort.

Dr. Fanger: Not only vaso-constriction and dilation but also sweating, shivering and activity level are important for the sensation of discomfort. But all these physiological factors are closely related to the thermal load of the body, which we correlated with subjection discomfort of 1300 test subjects.

Mr. P. Jay: Have you tried putting this instrument in a large number of common working environments, hanging beside it a mercury in glass thermometer and comparing the readings you get?

Mr. Madsen: If there were sun in the room you would obtain a higher temperature than with a normal thermometer. If there were draughts in the room you would obtain a lower value.

Mr. Jay: In a working environment such as a school or an office, have you any idea what is the practical range of these differences?

Mr. Madsen: I think it is impossible to say, because it depends on the environment, *Dr. M. Jokl:* What about sweating and respiration? Are they neglected?

Mr. Madsen: No, they are not neglected. The instrument is built for use at low activity levels, where there is little sweat for comfort, so the latent heat loss is taken into consideration by setting the water vapour pressure on the instrument. If you are sweating at a low activity level, the environment may be too hot, and you will read a positive PMV-value on the instrument.

Dr. Jokl: I am sweating slightly when I am in comfort. Is there a correction for this?

Dr. R.G. Nevins: The equation allows for this.

Dr. Fanger: It is necessary to measure the humidity separately, and then enter it on the dial.

Mr. G.A. Pickup: I presume this instrument is commercially available. How widely accepted is it in Scandinavia? Is it a research tool or is it for heating and ventilating engineers?

Mr. Madsen: It is mainly for the engineer to take field measurements. This is the first one. Only nine more are complete so far. They have all been sold in Denmark and Sweden. We will see how successful they are before starting a bigger production.