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Measurement of thermal comfort and discomfort

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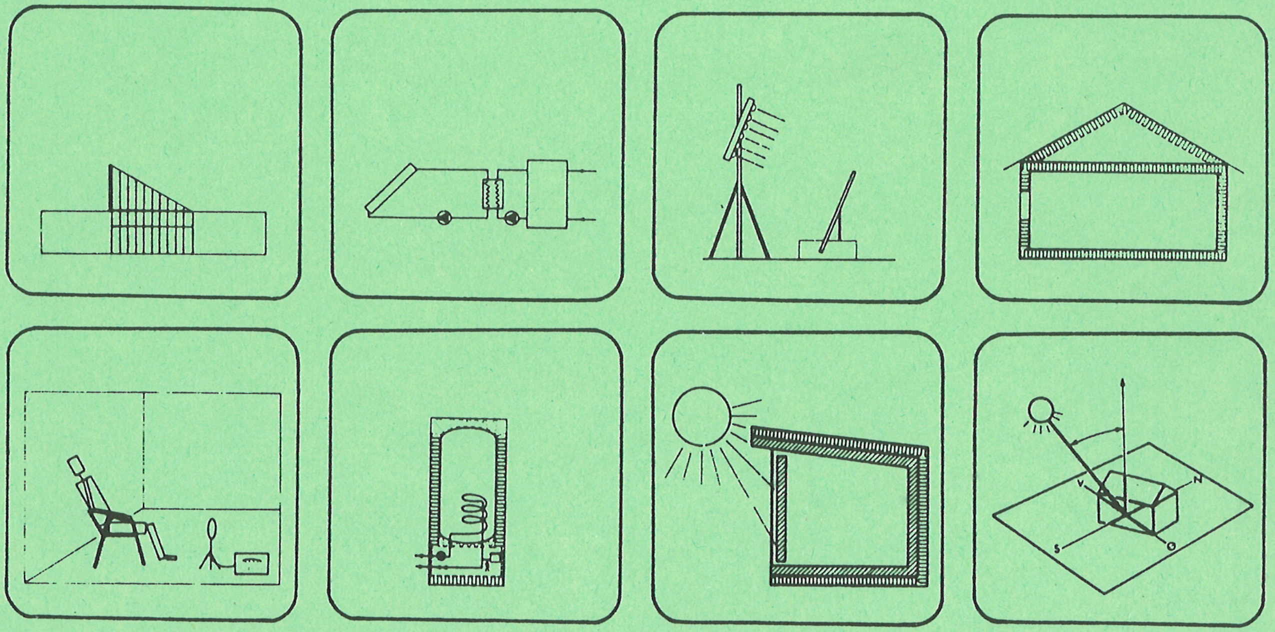

Measurement of thermal comfort and discomfort

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Abstract

Comfort criteria have been discussed, which by measurement, form the basis for determination of the expected thermal comfort. The disadvantages of traditional measuring instrumentation are pointed out and a better method is suggested for determination of a person's expected degree of general thermal comfort.

The lack of basis for a corresponding precise evaluation of the local comfort problems due to asymmetric radiation or draught is discussed. A couple of new parameters are given which, together with the existing knowledge, is deemed to give the best possible estimation of the degree of expected thermal discomfort due to asymmetry of the thermal field. Finally, a new instrument is described which can analyse thermal environments as well as measure these new parameters.

Measurement of thermal comfort and discomfort

The primary and most important requirement which has to be fulfilled for sustaining thermal comfort in an environment is that the heat balance of a human being should be acceptable. In other words, the balance between the heat produced by the body and the heat loss to the surroundings should be maintained at a suitable skin temperature.

comfort equation

The condition under which this can occur is expressed by Fanger's Comfort equation from 1967, [1].

PMV - index

If this equation is not fulfilled the expected degree of thermal discomfort can be expressed by Fanger's PMV - index from 1970 [2]. This index expresses in a single figure to what extent the general thermal comfort can be expected to be fulfilled in a given situation when the six thermal parameters are known. (See Fig. 1).

The necessary condition for maintaining

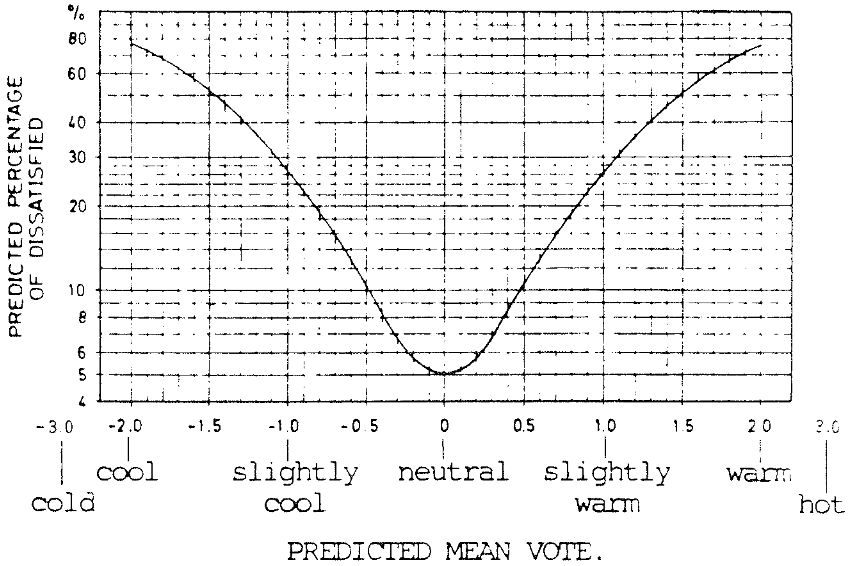

Fig. 1. Predicted Percentage of dissatisfied (PPD) as a function of Predicted Mean Vote (PMV) from [2].

thermal comfort is that the PMV index is as small as possible, preferably zero. This condition is, however, not always sufficient. There should also be no large local thermal asymmetries or gradients as they can cause unpleasant reactions from the exposed skin areas or parts of the human body. Thus it will always be possible in a cold room to find a distance from the fireplace where the heat balance for the body as a whole is acceptable, i.e. PMV = 0. However, a prolonged stay in the same position will rarely result in thermal comfort.

thermal asymmetry

It is possible nowadays to determine by measurement the extent to which the comfort equation is satisfied. As regards the local effects, there is still a lack of sufficiently reliable limit criteria to decide on the basis of measurements, whether these effects could lead to thermal discomfort. The whole comfort evaluation is further complicated by the general and the local comfort criteria being mutually dependent. For example, one could better tolerate a local cooling if the environment

comfort evaluation

is slightly too warm than if it is neutral or a bit too cold,[3].

Determination of the degree of thermal comfort

mathematical expression

The complete mathematical expression for calculation of the PMV value is given in [2] when the six thermal parameters are known. As the expression is rather complicated a direct calculation requires a computer. However, a number of tables and diagrams are given in [2] from which the PMV value can be determined using some corrections and interpolations.

tables and diagrams

Here a simple method is described which gives reasonably accurate results when appropriate measurements are taken. In this method the calculation is carried out in two steps, in that t_a, t_{mrt} and v are incorporated in a single parameter $t_{equivalent}$ after which the PMV value is determined with the help of three diagrams.

equivalent temperature

The equivalent temperature (t_{eq}) is defined as the common value of the air temperature and the mean radiant temperature which gives the same dry heat loss from a person at a wind speed equal to zero as the actual combination of these three parameters.

T_{eq} can be calculated with reasonable accuracy from this equation which also takes into consideration the influence of clothing on t_{eq}.

$$t_{eq} = 0.55\ t_a + 0.45\ t_{mrt} + \frac{0.24 - 0.75\sqrt{v}}{1 + I_{clo}} \cdot (36.5 - t_a) \qquad \text{(I)}$$

(where the last term should be taken into account only when v > 0.1 m/s).

It is now possible to determine the PMV value with the help of three diagrams. Firstly, the desired t_{eq} is found from the diagram in Fig. 2 i.e. the t_{eq} which gives PMV = 0 in a given situation. If this t_{eq} deviates

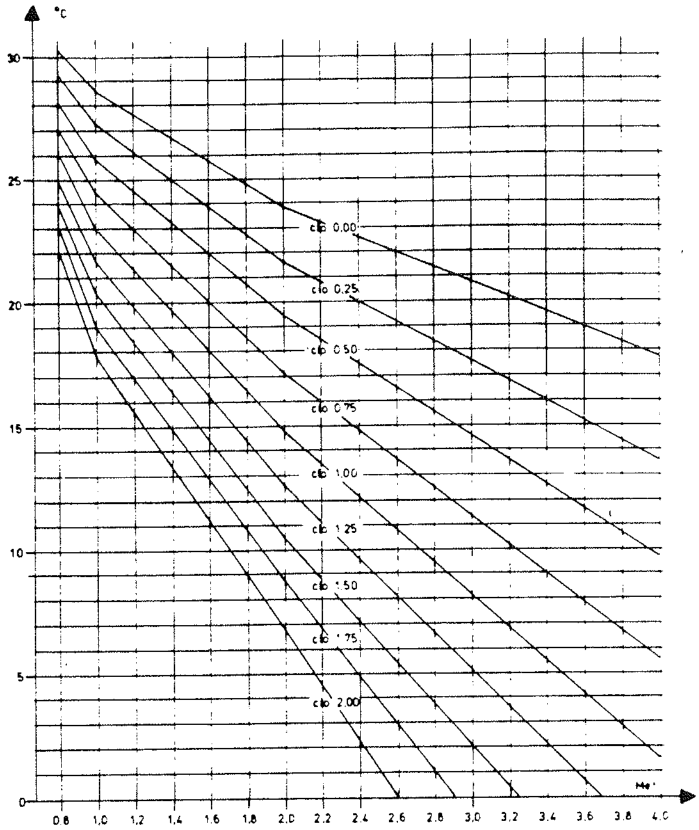

Fig.2. Diagram for determination of the wanted equivalent temperature when the activity level and the clothing are known.

from the actual value (which is determined with the help of equation I) the PMV value can be determined by the following expression:

$$PMV = A(t_{eq_{measured}} - t_{eq_{PMV=0}})$$

air humidity

where A can be determined with the help of the diagram in Fig. 3. The air humidity has a negligible influence on the PMV value in the comfort region. From the diagram in Fig. 4 it is possible to find a correction factor B which, when multiplied with the difference between the measured relative air humidity and the 50% RH (which is assumed in diagrams 1 and 2), gives directly the correction for the calculated PMV value.

determination of the PMV value

The complete expression for determination of the PMV value thus becomes

$$PMV = A(t_{eq_{measured}} - t_{eq_{PMV=0}}) + B(rf_{measured} - 50)$$

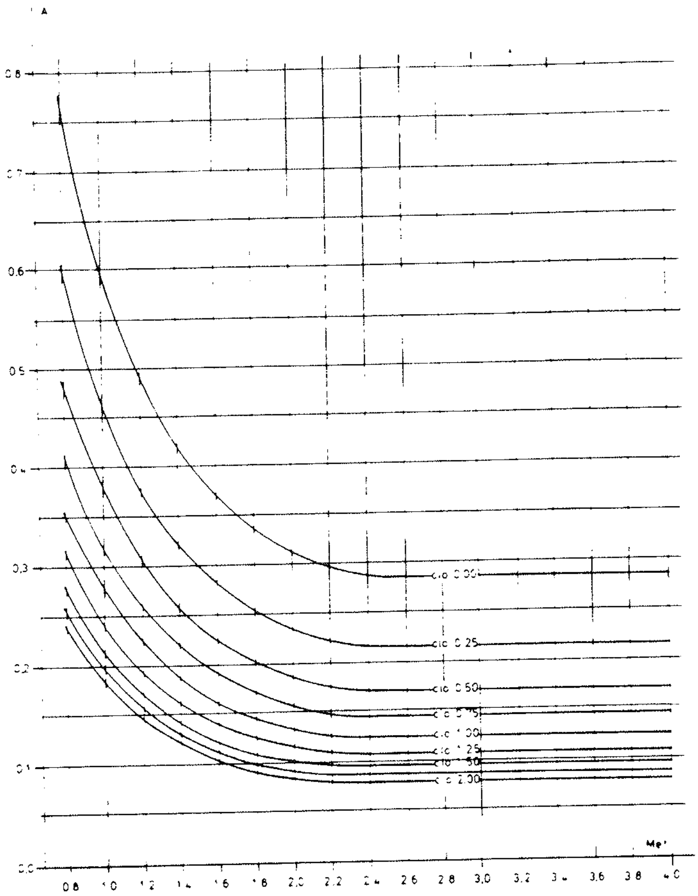

Fig.3. Diagram for determination of the factor which, when multiplied with the difference between the measured and the wanted t_{eq} gives the PMV value.

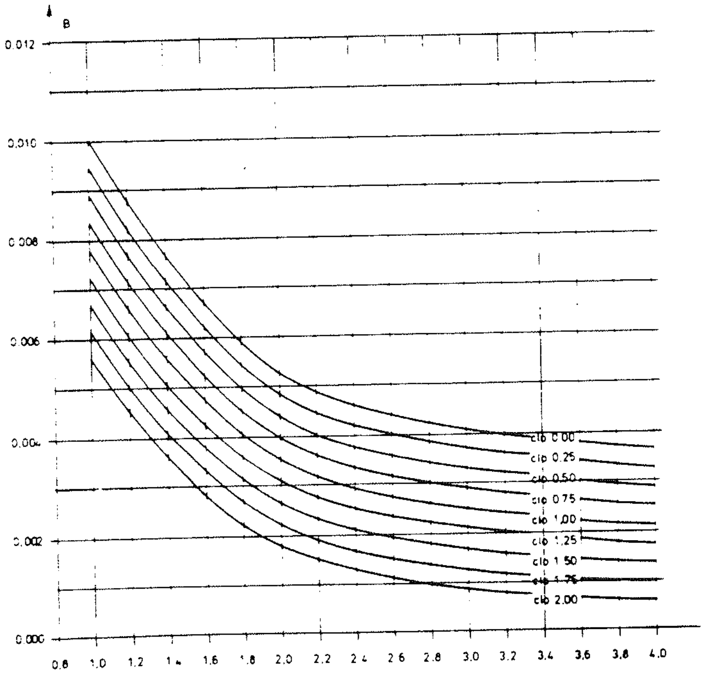

Fig.4. Diagram for determination of the factor which shall be used for the correction of the PMV value found, when the relative air humidity deviates considerably from the 50% which is predicted in Fig. 2 and 3.

Measurement of the thermal parameters

For all the above-mentioned methods the individual thermal parameters must be measured. Fig. 5 shows a typical set of measuring instruments.

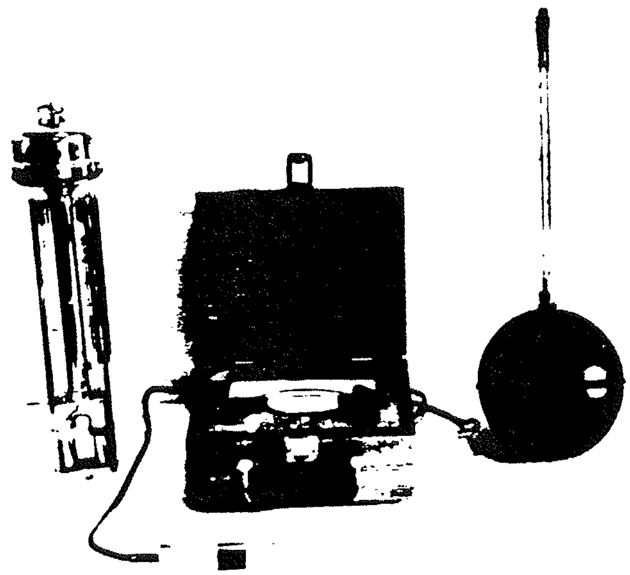

Fig. 5. Typical instruments to be used by measurements of the classical climatic parameters.

air temperature

The air temperature can be measured advantageously with the aspiration psychrometer shown, which simultaneously gives data for the calculation of the relative humidity or vapour pressure of the air. These parameters are easy and relatively quick to measure with good accuracy.

relative humidity

mean radiant temperature

The mean radiant temperature is defined as the uniform temperature of absolute black surroundings which will give the same radiation heat loss from a person as the actual environment under consideration.

globe

In most cases this is measured with a so called globe (see Fig. 5) which can, however, determine only t_{mrt} according to the definition with respect to a sphere. As a rule this will be acceptable but considerable errors globe measurements

can occur if there are large variations in the radiant temperature in different directions. For example, a point source will have approximately 4 times as great an influence on a person's PMV value if it is at a certain distance in front or back of a standing person than if it was at the same distance over the person. On the other hand the globe will give the same t_{mrt} for both the conditions. Another disadvantage with the use of a globe is its long time constant.

Fig. 6 shows a temperature history when the globe is instantly moved from one t_{mrt} to another. Finally it should be mentioned that the calculation of t_{mrt} from t_g requires knowledge of v as well as of t_a during measurement. As shown in Table (1) even small variations of v have a significant influence on the evaluation of t_{mrt}.

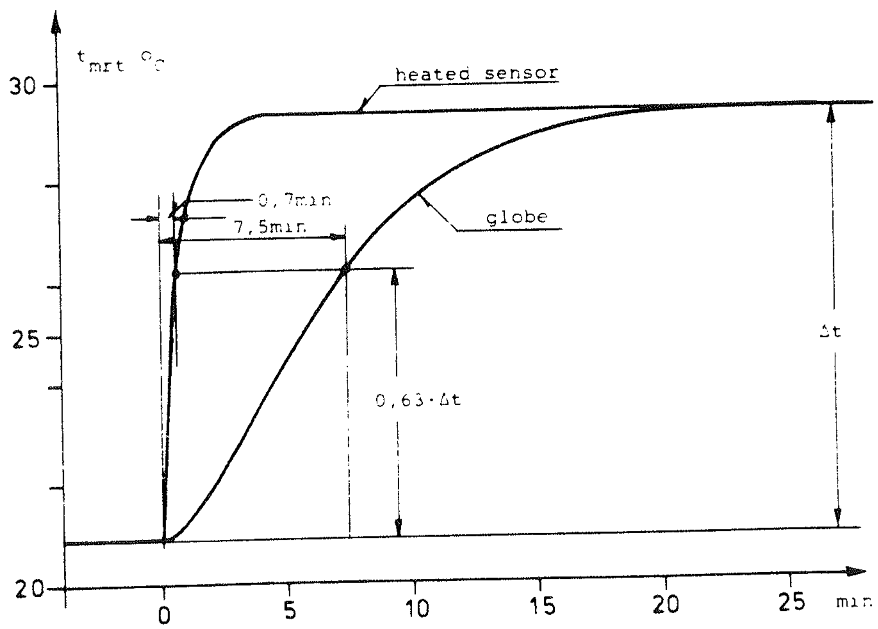

Fig. 6. Temperature history and time constant for respectively globe and comfort sensor at an instantaneous change of t_{mrt}.

v m/s	t_{air} °C	t_{globe} °C	t_{mrt} °C	$t_{equiv.}$ (0.6 clo)
0.05	20.0	22.0	23.0	21.4
0.20	20.0	22.0	24.2	20.9

Table 1. t_{mrt} and $t_{equiv.}$ calculated from measured values of v, t_{air} and t_{globe}.

air velocity

The air velocity is difficult to measure with reasonable accuracy especially at low values which are normally encountered. There are several reasons for this. Firstly, the velocities which have to be measured, as a rule fluctuate in amplitude and direction. Since most anemometers have deliberately a low time constant, a visual reading of the mean velocity is difficult. Improvement can be achieved if registration or integration is carried over a few minutes.

equivalent temperature sensor

All the above-mentioned difficulties in the measurement of t_{mrt} and v can be avoided if the equivalent temperature is measured instead with a sensor, which does not measure the individual thermal parameters, but rather the overall influence of these on the heat loss from a body which simulates a person from a thermal point of view. Such a sensor is described in [4] and [5] and shown on Fig. 7. Its time constant is shown i Fig. 6 and can be seen that it is approximately ten times faster than the globe which is the only practical alternative available today. The low time constant is caused by the sensor having an over-temperature compared to the environment, which results in a greater heat exchange and hence a rapid temperature change. This effect is further amplified because the power emitted by the sensor is controlled in such a way that it increases when the environment becomes cooler and reduces when the

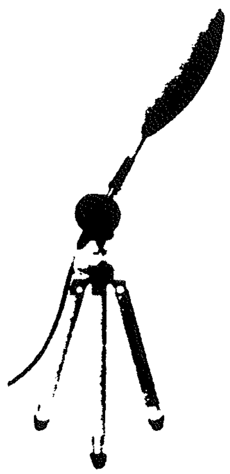

Fig. 7. Heated comfort sensor.

temperature rises until a steady state is reached.

Direct Measurement of Thermal Comfort

determination of PMV - value

As described in [4] and [5] it is possible to determine accurately the PMV as well as the PPD values (see Fig. 1) directly in a particular environment with the use of a new measuring instrument.

new instrument

The instrument is designed such that it is possible to select the activity level and the clothing which is relevant in a given situation. If it is desired the vapour pressure of the air can also be selected on the instrument. With the help of the above-mentioned sensor the thermal environment of the room is determined, after which the PMV and PPD values are calculated using a processor and displayed on a digital meter. Furthermore, the equivalent temperature of the room can be directly read on the instrument and (as a new innovation) the number of degrees by which t_{eq} should be altered to bring the PMV value to zero.

activity level

clothing

thermal environment

Thermal discomfort due to local thermal effects

In course of time a number of limit criteria have been suggested for local thermal effects which humans can accept before thermal discomfort is expected [6, 7, 8, 9].

In [10] a hypothesis is put forward where the parameters (governing the discomfort caused by local thermal effects) are the amplitude and variation of the heat flow through the exposed skin area, and this area itself.

heat flow through the skin

The existing limit criteria are, however, not given as a maximum heat flow but as a maximum radiant temperature difference in the case of thermal asymmetry. For undesired air flows (draught) the limits are quoted as a rule in terms of the maximum permissible air velocity.

Consequently, for the time being it would be most relevant to measure these parameters when a given environment has to be analysed for evaluation of the risk for local thermal discomfort. One would obtain a better basis for a general evaluation of the indoor climate if the classical thermal parameters can simultaneously be determined.

A new instrument for the analysis of thermal indoor climate

The philosophy behind the instrument described below is the same as that used for the development of the above-mentioned comfort meter: the sensor should be developed which can simulate the heat exchange as realistically as possible between the skin and the environment at the place where discomfort is expected to occur. The measuring instrument is then set up to calculate the data from the sensor signals which are expected to be of interest, when the thermal quality of a given room has to be analysed.

a new sensor

measuring instrument

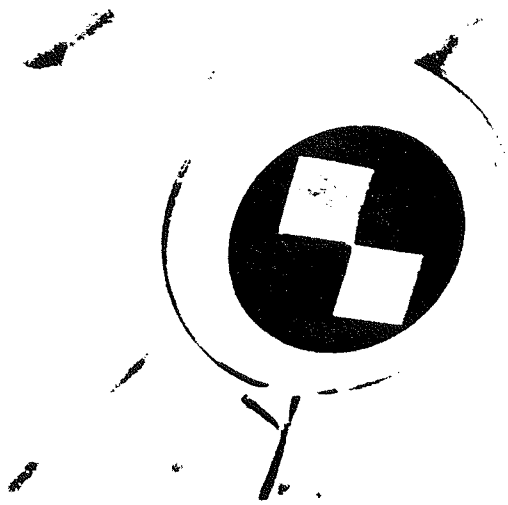

Fig. 8. A new sensor designed for measurements of different local discomfort parameters.

In the present version, the instrument (Fig. 8 and 12) can determine the following parameters:

1) air temperature (t_a)
2) mean air velocity ($\bar{v}$)
3) radiant temperature in two half-rooms (prt) and further
4) vector radiant temperature (vrt)
5) the vector equivalent temperature (vet)
6) the equivalent air velocity (eav)

The last four are described in the following in some detail.

The design and operation of the sensor

In principle the sensor must consist of a plane element that has the same surface temperature.

sensor properties

radiation properties,
heat capacity
and thermal conductivity
as the human skin in thermal comfort. Such a plane element will statically and dynamically simulate the local heat exchange between the skin and the surroundings.

sensor heating element

A sensor can be constructed from a thin ceramic disc with a surface having the same radiation absorption range as the human skin. On the reverse side of the disc a platinum film resistor of 100Ω at $0^{o}C$ is mounted. This resistor can be used both to heat the sensor and to control its temperature.

painted or gold-plated sensor elements

Since the sensor, however, should yield information for the calculation of all the six mentioned parameters a slightly more complicated design is necessary as shown i Fig. 8. Four ceramic discs are mounted on each side of a 10 mm insulation sheet. Two of them are painted and will emit heat by radiation and convection whilst the other two, being gold plated, will therefore emit heat only by convection.

temperature dependant resistor

For measurement of the air temperature the sensor is equipped with a temperature dependent resistor - a thermistor which has two functions:

measuring bridge

1) it can be used with a measuring bridge to display the air temperature on a meter,
2) it can also be used to control the power fed to the four discs such that their temperature is always equal to the actual air temperature plus 10°C. The 10°C corresponds to a typical overtemperature of the bare skin at normal indoor temperatures (23 - 24°C).

overtemperature

The above-mentioned thermal parameters can be determined by the sensor in the following way.

Mean air velocity ($\bar{v}$) (m/s)

Assuming that the gold plated discs reflect all radiation and that there are no boundary losses, the heat loss to the environment would only be caused by convection. Furthermore, the heat loss from each set of discs will depend only on the air movements around the sensor since the discs have a constant overtemperature of 10°C. Fig. 9 shows the relation between this heat loss and the air velocity along the sensor.

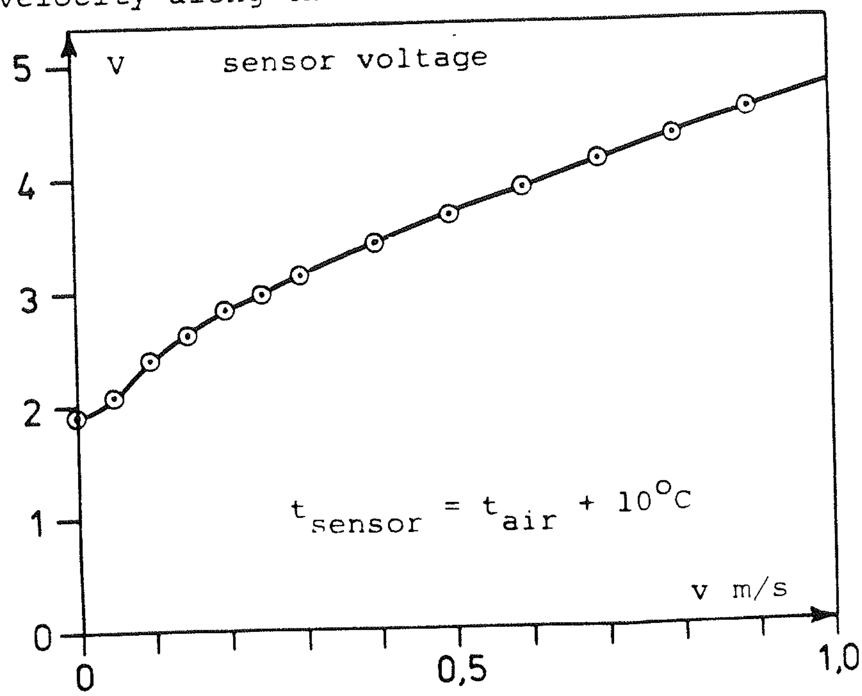

Fig. 9. Heat loss from goldplated sensor element as a function of the air velocity along the sensor.

During measurement of v the surface of the sensor should be parallel to the direction of the velocity; this will be the case, when the same power is fed to the two sets of discs or in other words when the velocity measured is equal on both the sides.

correction of the measured value

An electronic circuit built in the instrument corrects for the imperfections in the reflection from the surfaces and their boundaries and converts the power fed to the surfaces into signals which can be directly read on two meters in terms of the mean air velocity along the corresponding surfaces in m/s.

Plane Radiant Temperature (prt) (^{o}C) [11] or Directional Mean Radiant Temperature (DMRT) [12]

The sensor can measure directly the radiant temperature in the 2 half-rooms of the environment which is divided by a plane through the sensor. This measurement is obtained by determining the difference between the power fed to the painted and the gold-plated discs respectively. The difference is due to the heat exchanged by radiation between the painted discs and the environment since the heat loss by convection is the same for the painted and the gold-plated discs because of their relative positions.

The relation between the difference in the power fed to the discs and radiant temperature can be calculated. However, due to the boundary effects and uncertainty in the emission values specified, the most accurate determination of radiant temperature can be obtained by calibration using a number of known surface temperatures.

calibration

In spite of this a correction for the measurement is necessary. This is because the radiation heat that is exchanged between two bodies at a constant temperature difference (e.g. $10^{o}C$) increases approximately by

1 percent when the absolute temperature rises by $1^{O}K$. After correction the radiant temperature (prt) for each of the 2 half-rooms can be read on two meters. The actual air temperature should be added to the figure read on the instrument to determine prt. In most cases it is, however, of greater interest to know whether prt is higher or lower and this can be read off directly.

plane radiant temperature

With the instrument described here the mean radiant temperature cannot be measured directly. It can, however, be found quickly as an average of the 6 prt values obtained by measuring with the sensor in three mutually perpendicular directions. Such a measurement is both quicker and more informative than a conventional measurement with a globe.

mean radiant temperature

Thermal Asymmetri

As a measure of the degree of thermal asymmetry in a radiation field, Griffiths and McIntyre [13] have defined the vector radiation temperature (vrt) as the difference between the radiant temperature on the two sides of a flat element when the element is oriented to give the largest possible difference.

vector radiant temperature

This vrt can be determined directly by this instrument simply by measuring the difference between the radiant temperature between the two half-rooms "seen" by the sensor.

asymmetry caused by air velocity

Thermal asymmetry can, however, also be caused by air velocities; thus it would be reasonable to include a measurement of the difference between the power fed to the painted discs on the two sides of the sensor. This difference will correspond to the difference between the heat flow through two opposite faced skin elements on the body when these elements have the same orientation as the surface of the sensor. Ideally this difference should be given in terms of a heat flow, but in analogy with the above-mentioned radiation asymmetry (vrt) the measurement result would be more relevant if it is given as a temperature difference for the corresponding heat flow. The result is a vector equivalent temperature (vet) which gives the difference between the equivalent temperature in the two half-rooms "seen" by the sensor.

vector equivalent temperature

In reality, the "vet" parameter is the one that is best suited to give the degree of thermal asymmetry. The reason why it is still not used is because the investigations up till now have either been with asymmetric radiation fields or with asymmetric convection fields and not with the combinations which are encountered in practice.

Draught Measurement

Draught is defined in [9] as an undesired local cooling of the body due to air movement, and it is proved, that the degree of thermal discomfort caused by draught is depending on the local air's:

draught parameters

1) temperature, relative to the room air temperature
2) mean velocity ($\bar{v}$)
3) velocity variation ($\frac{v_{max}}{\bar{v}}$)
4) frequency of this variation.

No index has been given in [9] for the determination of the degree of discomfort. Instead a number of examples have been given for permissible velocities which will cause 5, 10, 20, or 30% of persons to be thermally dissatisfied.

In [10] the following unit is given which takes all the four mentioned factors into account:

equivalent air velocity

The equivalent air velocity (eav) is a completely uniform velocity which in an isotherm environment will cause the same

degree of thermal discomfort as the actual combination of the local air temperature and mean velocity as well as of the amplitude and frequency of possible velocity variations.
The measuring instrument described here can directly determine eav. By equipping the instrument with an extra air temperature sensor, which is placed outside the draught zone, it is possible to determine the local air temperature's deviation from the room air temperature. The mean air velocity measurement has been discussed earlier. Fig. 10 shows how the influence of the variation and frequency of the air movement is incorporated in the measurement of eav.

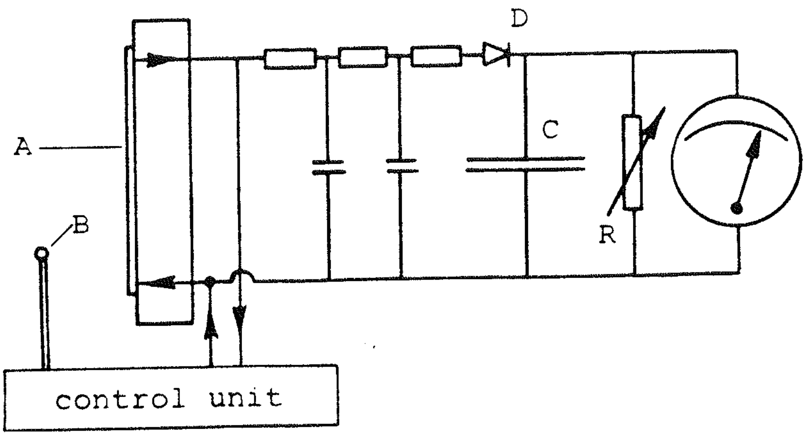

Fig. 10. A simplified diagram showing the selection of the critical air velocity frequencies.

The voltage over the heating element of the gold-plated discs is low pass filtered to remove the voltage variations due to quick air velocity changes (> 1 Hz). Slower variations will pass through and charge the capacitor (C) through diode (D) whereby the voltage over the meter will be greater than that corresponding to the mean velocity. If the velocity variations are very slow (<< 0.1 Hz) C will be discharged through the resistor (R).

The deflection will become smaller and again approximate the mean velocity along the discs of the sensor. Hereby, this contribution to the mean velocity giving an additional meter deflection is proportional to the amplitude of the velocity variations and secondly it is dependent on frequency as shown by the curves in (9).

uncomfortable

correlation between the sensation of draught and the frequency of the local air movement $\bar{v}$ = o.3 m/s. from [9].

not uncomfortable

maximum heat flow through receptor o.2 mm under the skin surface, dependant on the frequency of a temperature change at the skin surface. from [10].

eav and $\bar{v}$ measured simultaneously with the described instrument

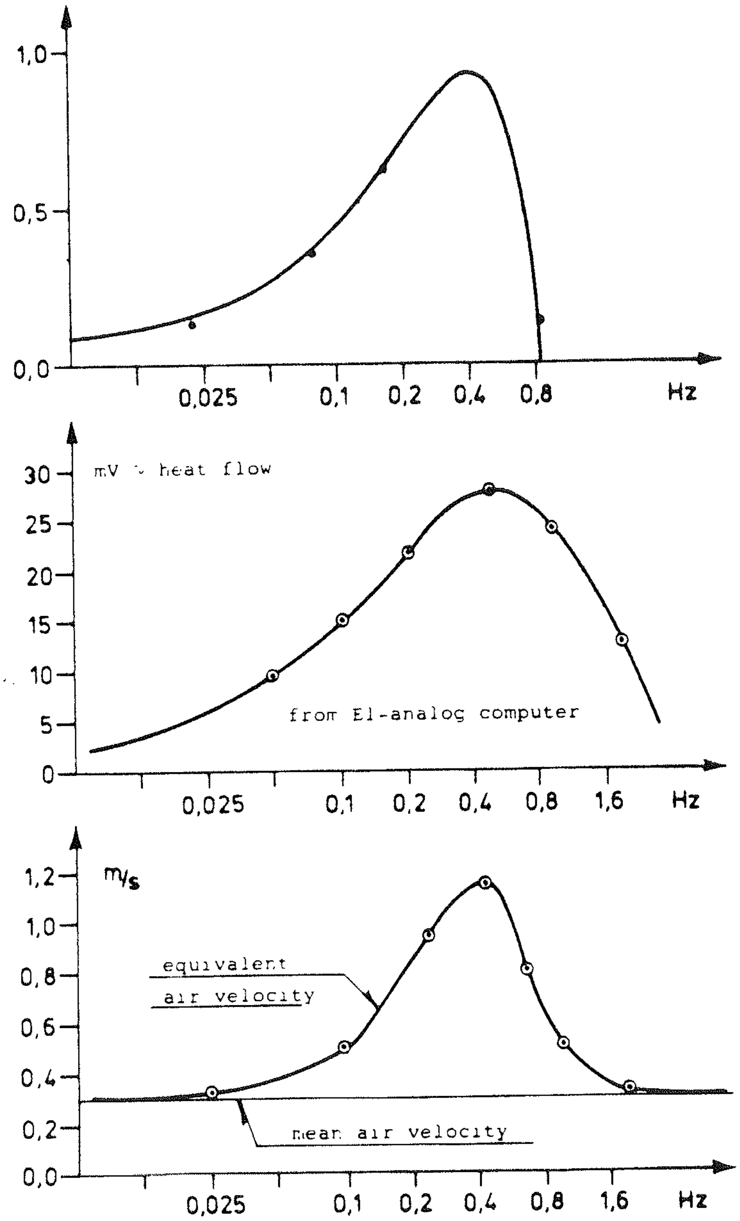

Fig. 11. Comparison between comfort votes, heat flow through the skin and equivalent air velocity, as a function of the frequency of a fluctuating air flow $\bar{v}$ = 0.3 m/s.

Fig. 11 shows three frequency characteristics. The upper curve shows the relation between the comfort votes and frequency of air variation from [9]. The middle figure shows the dependence of the maximum heat flow through the skin thermoreceptor on frequency from [10].

The bottom curve shows the equivalent air velocity as a function of frequency, when the air temperature mean air velocity and the degree of fluctuations is kept constant. The curve is a measurement result obtained with the new instrument.

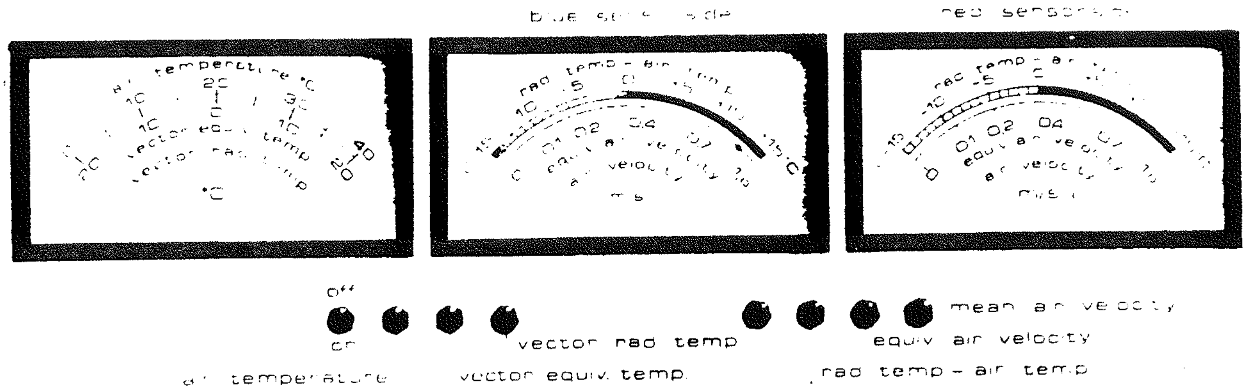

Fig. 12. Prototype of a new instrument for determination of local thermal comfort parameters.

Conclusion

The measuring instruments used in most cases for the evaluation of the indoor thermal environment is still rather primitive. Especially the measurement of the mean radiant temperature is time consuming and inaccuracies under certain conditions can be significant. However, measuring instrumentation is available now which makes it possible to determine the expected degree of general thermal comfort quickly and with good accuracy taking all the relevant parameters into account.

There still exists no available index or limit criteria for the local thermal effects which can directly give the expected degree of thermal discomfort. This is because in each of the investigations carried out up till now, the influence of only a single parameter on the comfort perception has been taken into account. Naturally the result has been that the comfort limit has been given as a maximum acceptable value of that specific parameter. In reality, the local thermal discomfort in most cases is caused by a combination of different thermal effects and comfort limits should therefore be laid down (similar to the PMV index) relative to the person's expected subjective reaction under all normal possible combinations of local thermal effects.

Even today there are no standard measuring methods for determination of the degree of thermal asymmetry or draught. Neither are there any measuring instruments on the market which are particularly adapted for these measurements.

The measuring instrument described here is developed as an aid to fulfilling this need. Just as in the case of the comfort meter, the instrument has been constructed with the aim of simulating a person's heat exchange with the surroundings.

Whilst the comfort meter takes into consideration the heat loss of a person as a whole, and hence of the central temperature perception, the comfort analyzer aims at simulating a person's peripheral temperature perception.

There is still a need of a "coordinator" which can assimilate signals from the two instruments to obtain an absolute value which gives a person's overall perception of a thermal environment. For such a "coordinator" to be constructed more experimental results are required which can form the basis for establishing subjective comfort criteria for local thermal effects. Besides, further investigations are necessary to determine how different combinations of central and local thermal effects affect a person's perception of thermal comfort.

Until such investigations are available it is deemed that the parameters discussed here are the most suitable for characterising a room's thermal condition.

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DISCUSSION

M.A.Humphreys
Building Research
Station, UK

May I enquire further about the 10° overtemperature of the new sensor? I believe that the overtemperature of the clothed body is nearer 4° than 10°. Also the size of the sensor is small compared with the body. Taken together will not these factors result in an overestimation of the effects of convection?

T.L.Madsen

Supposing it is the naked or lightly clothed body parts which most frequently cause local thermal discomfort, then 10° overtemperature is a better choice than 4°.

At the same time the 10° overtemperature makes it possible to measure at relatively high radiation temperatures. Such high radiation temperatures would necesitate cooling of the sensor elements if these were only 4° warmer than the air.

It is correct that the sensor is small compared to a person and that this will cause an overestimation of the effect of convection. However, the measurement of the indivdual parameter is carried out after calibration of the sensor under realistic but known thermal conditions. Thus, the relation between the heat loss by radiation and by convection has no importance when it is known and can be included in the transformation of the measuring values to the pointer deflection in the instrument.

Only by measuring the vector equivalent temperature can an overestimation of the importance of the air velocity compared to a person take place. This parameter is thought to give a more correct statement of the thermal asymmetry than the vector radiant temperature which completely ignores the importance of any air velocity.

E. Rødahl
Technical University of Norway

The sensing element is plane. The human body is more similar to a globe or a cylinder. Have you reflected on the different mode of heat exchange by radiation from a small sphere and a small plane element?

T.L. Madsen

There are several reasons for the chosen form og the sensor element.

1. Technologically it is a simple one.

2. A known radiation asymmetry will give a greater maximum difference on the two sites of a flat sensor

than on two opposite directed hemispheres. This gives a more exact determination of the maximum radiation asymmetry and its direction.

3. Most of the assymmetry limits stated so far are related to flat elements.

4. It must be remembered that this sensor is intended for thermal analysis of the environmental parameters. Measurement of the total thermal effect on the human body can most easily be carried out with the sensor in figure 7. It is shaped to give a simulation of the radiation exchange between man og the environment.

5. When the plane radiation temperature is known in the six main directions it is furthermore possible, for instance by the diagrams in ref. (2), to calculate the radiation effect on a standing or seated person.

M. Rolloos
Delft University
of Technology, NL

1. When will the new measuring instrument for local discomfort appear on the market?

2. Will it then no longer be necessary to use subjects in climate chamber studies?

T.L.Madsen

1. It is difficult to answer exactly. The instrument is being further developed, but some years will pass before the final model is available on the market.

2. It will still be necessary to carry out climate chamber investigations with test persons.

These investigations will also in the future form the basis of a still better determination of the limits between thermal comfort and discomfort in simple as well as in more complex environments.

First when these limits are known can the instruments described here be used to predict the human response in a given environment in practice.