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NEW INSTRUMENTS FOR MEASURING THERMAL COMFORT

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MEASURING THERMAL COMFORT

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Les instruments de mesure du confort thermique

RÉSUMÉ : *Au cours des dernières années on a reconnu généralement que le confort thermique à un certain niveau d'activité était étroitement lié à la température moyenne de la peau ou à la résistance thermique de la peau et à la transpiration lorsque le corps était en équilibre thermique avec le milieu ambiant. L'échange de chaleur entre un corps quelconque et son environnement dépendant de sa forme et de ses dimensions on conçoit qu'un instrument approprié à la mesure du confort thermique doivent avoir la même forme et les mêmes dimensions que le corps humain.*

Comme mesure du degré de confort thermique, ou plutôt d'incorfort, on peut utiliser la différence entre la perte de chaleur sensible correspondant au confort thermique à un certain niveau d'activité et la perte de chaleur sensible réelle dans le milieu thermique à étudier.

Dans les milieux thermiques non uniformes le confort thermique dépend aussi dans une certaine mesure des écarts de la température de la peau pour diverses parties du corps à partir de ceux correspondants au confort thermique.

Dans ce rapport on décrit deux instruments qui ont été mis au point au laboratoire de l'A. en application des principes ci-dessus :

1. *Le mannequin thermique qui a approximativement les dimensions et la forme d'un être humain et qui est spécialement adapté à l'analyse des milieux thermiques non uniformes.*
2. *Le compteur de confort thermique qui est un instrument plus petit et plus commode et qui peut être facilement adapté à divers niveaux d'activité et divers vêtements et qui donne le degré d'inconfort thermique.*

INTRODUCTION

It is well known that the deep body temperature is kept almost constant at approximately 37 °C, even if the thermal variables of the environment are varying within wide limits. But within these wide limits there is only a narrow interval or zone which will be felt thermally comfortable or neutral. The position of this zone will depend

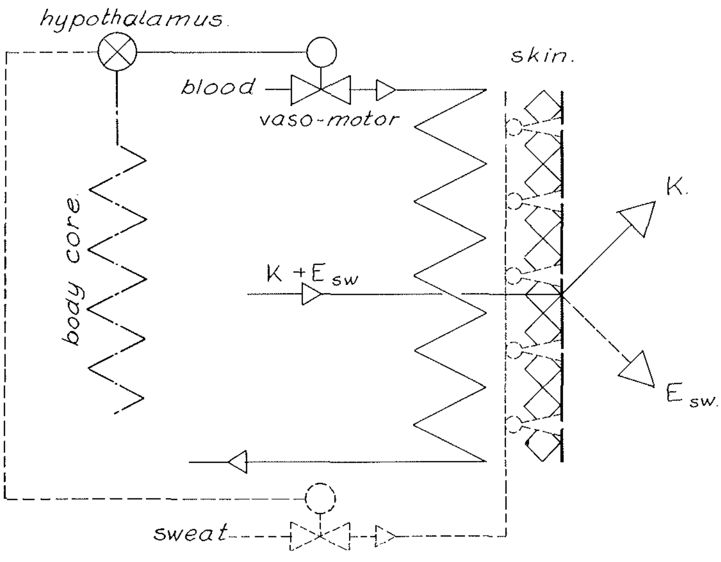

Fig. 1 — Physical thermoregulation.

the body's thermal effector mechanisms: vasodilation and vasoconstriction, sweat secretion and shivering, figure 1.

The comfort zone can be refered to one of the following thermal characteristics:

1. The operative temperature of the environment;
2. The mean surface temperature of the clothed body;
3. The mean skin temperature;
4. The deep body temperature.

While changes in the thermal environment mainly will be felt by the thermal receptors of the skin, the general feeling of warmth will be related to the deep body temperature. If we consider the human thermoregulating system as a simple proportional control system, figure 2, we shall postulate that under steady state conditions the degree of thermal discomfort is proportional to the offset or load error of the thermostat, the regulated quantity or controlled condition being the deep body temperature.

$$\text{Offset} = \text{actual value} - \text{set point}$$

The set point will increase with the activity level or metabolism, and it will follow a diurnal variation.

This present merely a phenomenological and engineering point of view and do not pretend to cover physiological realities.

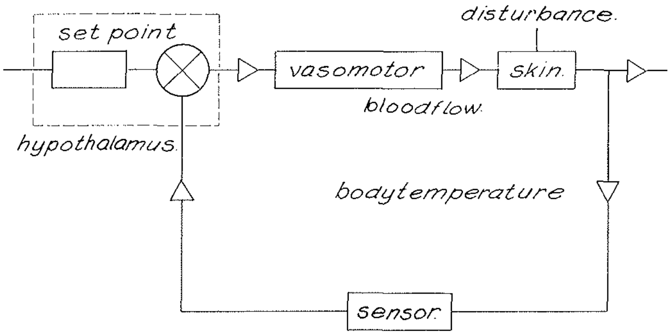

Fig. 2 — The human thermoregulating system within the comfort zone considered as a simple proportional control system.

We shall now consider a person who is in thermal comfort at a certain activity level, which means that the offset is zero. If we change his thermal environment we change his thermal load. In the terminology of the control engineer this change is termed disturbance. If the disturbance is kept constant it will cause a permanent offset, the value of which will depend on the amplification in the control loop. The offset is given by the following expression:

$$\Delta T_b = \frac{k}{1+\alpha} \Delta H \qquad \text{(I)}$$

where

ΔT_b the offset;
ΔH the disturbance;
α the amplification factor;
k a factor depending on the units used for ΔT and ΔH.

human thermoregulating system, if the offset was known for a given disturbance. However, it has not been possible to show such a dependence. This might be due to a high amplification. For our purpose this is of minor importance, as what we are really interested in is the relationship between the disturbance and the degree of thermal discomfort. That such a relationship exists has been shown by Fanger [1]. The principal relationship is shown in figure 3.

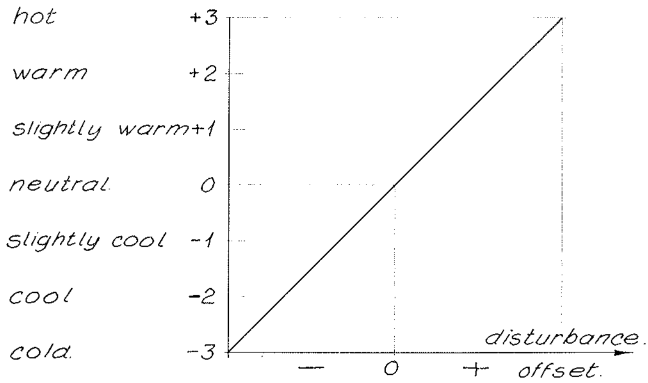

Fig. 3 — The degree of thermal discomfort as a function of the load error (disturbance).

Heat balance and disturbance

The heat balance equation for the human body can be written as follows:

$$M \pm W = H = E_{ex} + E_{sw} + K \quad \text{(II)}$$

$$K = R + C \quad \text{(III)}$$

where

M the metabolic rate;

W the external work;

H the internal heat production;

E_{ex} the total respiration heat loss;

E_{sw} the latent heat loss through the skin;

K sensible heat loss through the skin;

R the heat loss by radiation from the clothed body;

C the heat loss by convection from the clothed body.

To indicate values of the quantities mentioned, which correspond to thermal comfort, the index *c* will be used, and for the actual values index a will be used.

The disturbance is defined as the difference between the internal heat production and the heat loss to the actual environment from a person hypothetically kept in thermal comfort at the actual activity level. Using the above mentioned quantities the disturbance is given by the expression:

$$\Delta H = H^a - (E_{ex} + E_{sw})^c - (R + C)^c \quad \text{(IV)}$$

While E_{ex} is almost independent on the degree of discomfort, E_{sw} will increase rapidly with the degree of discomfort on the warm side. With good accuracy E^c_{ex} and E^c_{sw} are linear functions of the activity level and independent on the ambient air

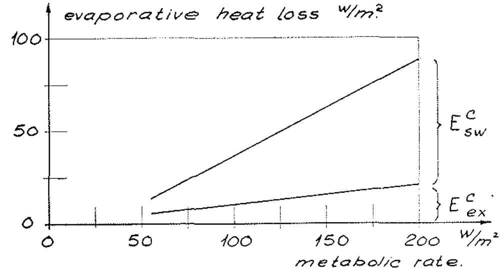

Fig. 4 — E^c_{ex} and E^c_{sw} as functions of the activity level (metabolic rate).

temperature and humidity, figure 4. In the following we shall see, how the dry heat loss $K^c = (R+C)^c$ can be determined. For this purpose a block diagram of the body heat loss is drawn in figure 5.

Applying Ohm's law on the steady state heat flow from the body core to the environment we find:

$$T_s = T_b - (E_{sw}+K) \cdot I_s$$

$$T_{cl} = T_s - K \cdot I_{cl}$$

$$T_o = T_{cl} - (R+C) \cdot I_o$$

where

T_b the deep body temperature;
T_s the mean skin temperature;
T_{cl} the mean temperature of the clothed body;
T_o the operative temperature of the environment;
I_s the insulation of the skin;
I_{cl} the insulation of the clothing;
I_o the insulation from the clothing surface to the environment at the uniform temperature T_o.

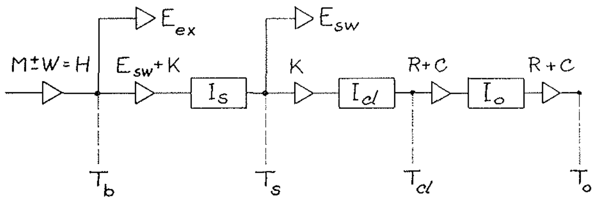

Fig. 5 — Blockdiagram of the body heat loss.

The heat loss by radiation and convection can be calculated from standard formulas, when the mean surface temperature is known together with the air temperature, the air velocity and the mean radiant temperature of the environment with respect to the person in question.

To calculate the combined heat loss $K^a = (R+C)^a$ from the person in hypothetical comfort the mean surface temperature T^c_{cl} of the clothed body must be known. As will be recognized from the heat flow diagram this temperature will depend on the

the following formula:

$$T^c_{cl} = T^c_s - (R+C)^a\, I_{cl}$$

where

$$T^c_s = T_b - (H^a - E^a_{ex})\, I^c_s$$

The insulation I^c_s of the skin in the comfort condition is a function of the activity level and can be found from figure 6. I^c_s cannot be measured directly but is determined by measuring the mean skin temperature and metabolic rate of subjects in thermal comfort at various activity levels. T^c_s can therefore also be taken directly from such measurements. However in practice it is rather tedious and difficult to measure the air velocity and mean radiant temperature with sufficient accuracy. Therefore it seems more appropriate to measure the combined radiation and convection heat loss directly

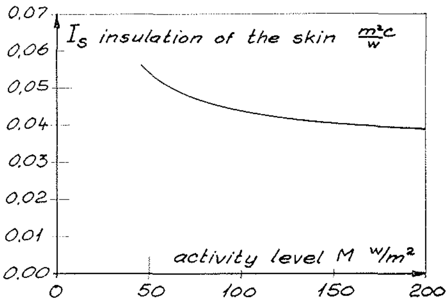

Fig. 6 — Insulation of the skin in the comfort condition as a function of the activity level.

by measuring the energy input which is necessary to keep the surface temperature of a full size body shaped instrument at the value corresponding to thermal comfort. Even a smaller instrument could be used as long as it has the same radiation and convection properties as the full size instrument. In the following two such instruments which have been constructed at our laboratory will be described.

Thermal mannequin

The instrument is shown on figure 7. As can be seen from the photo the various parts of the body have been simplified in shape and is made up either of planes or cylinders. Each segment is compounded of two 1 mm aluminium plates glued on each side of a 2 mm thick plate of polystyrene foam. To the inside plate is glued a resistance grid. The temperature of the plate is kept constant at a set point by an electronic control system. The outer plate is painted in a colour with the same emissivity as the skin. The temperature across the insulation which has a value equal to that of the skin I^c_s at an activity level corresponding to sedentary or light work, is measured by means of thermo couples. The total number of heat flow meter segments are 37. This allows a very detailed analysis of the heat loss from the various parts of the body. In a non-uniform thermal environment one may expect that the degree of discomfort may depend also upon the degree of non-uniformity and not only on the disturbance as defined earlier. The instrument is specially suited in studies to elucidate this problem, and also in the study of the thermal environment produced by various types of heating, cooling and ventilating systems.

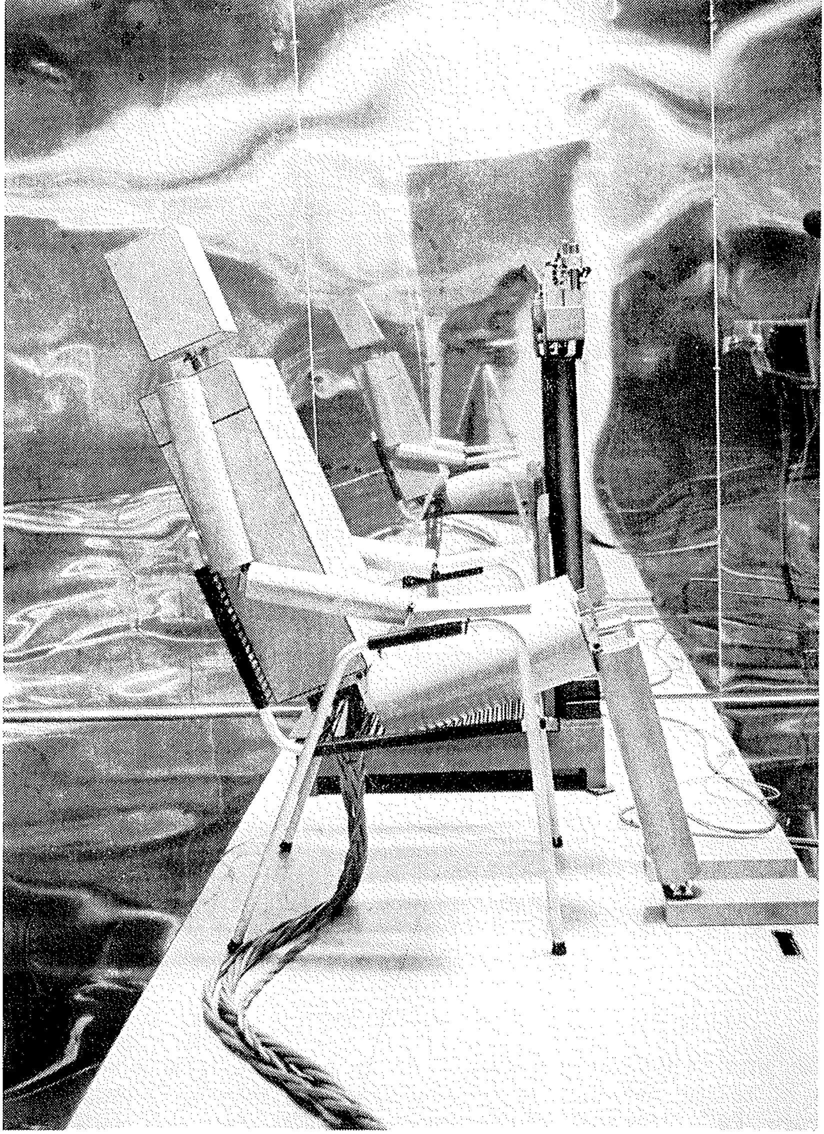

Fig. 7 — The thermal mannequin in a climate room.

In figure 8 the measured combined heat loss by radiation and convection from the mannequin is compared with the calculated values using the following standard formula:

$$R+C = 3{,}94 \cdot 10^{-8}\left[(T_s+273)^4-(T_{mrt}+273)^4\right]+2{,}38 \cdot (T_s-T_a)\;1{,}25\;(W/m^2) \quad (V)$$

where

T_{mrt} mean radiant temperature of the environment;

T_a air temperature.

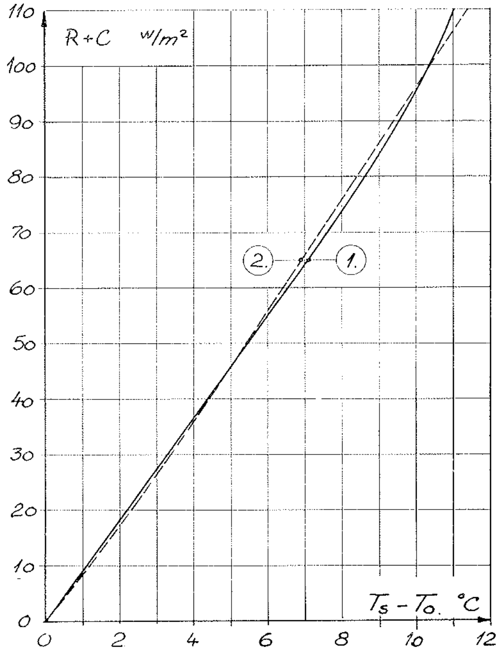

Fig. 8 — The combined radiation and convection heat loss from the mannequin:
1. Measured in climate room; 2. Calculated from (V).

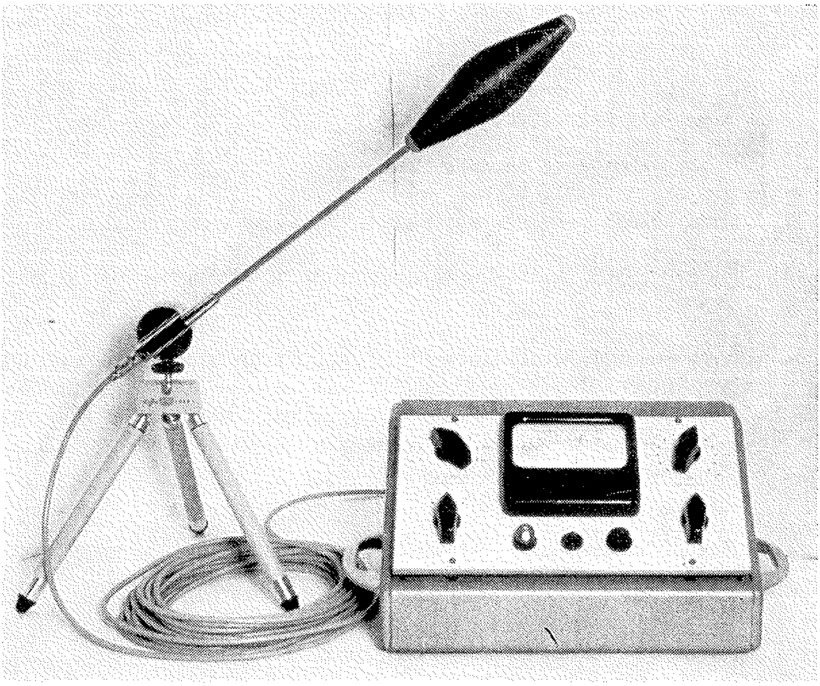

Fig. 9 — The thermal comfort meter.

various clothings with different insulations.

The disturbance is found in accordance with the equation (IV), where the combined heat loss $(R+C)^c$ is measured by the mannequin. The instrument can also be used to measure the operative temperature of a certain environment.

Thermal comfort meter

Although the mannequin must be considered as the most correct instrument for measuring the thermal environment with respect to a person, a smaller and for practical purposes more handy instrument has been constructed, figure 9. Its size and shape have been chosen so that the relationship between the heat loss by radiation and convection is the same as for the human body. The sensing element is electrically heated, and the surface temperature is controlled at a value corresponding to thermal comfort at the actual activity level. The disturbance is measured directly in accordance with the equation (IV) and can be read on the instrument scale corresponding to figure 3.

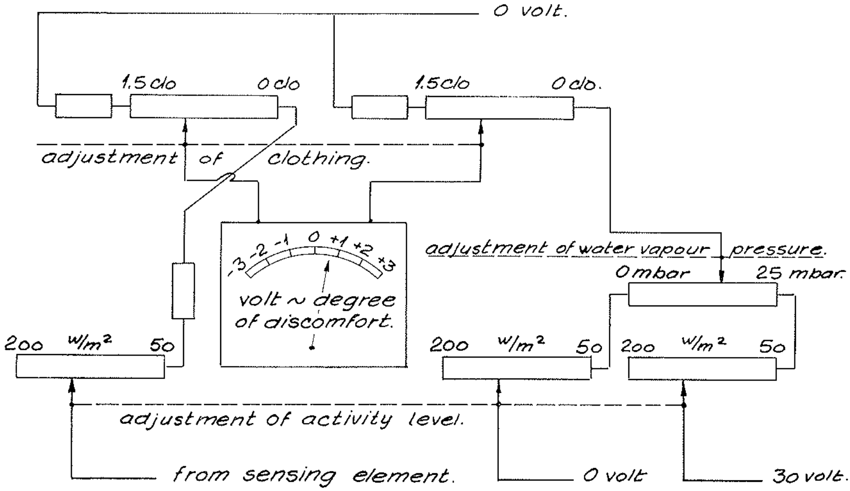

Fig. 10 — Diagram of the electrical resistance network of the thermal comfort meter.

The activity level and the insulation of the clothing can be set on the instrument. To get a more correct value of E^c_{sw} the partial water vapour pressure of the air can be set on the instrument. Figure 10 shows the electrical resistance network, which performs the necessary calculations. The instrument can also be used to measure the operative temperature of a given environment.

REFERENCES

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

J. J. KOWALCZEWSKI (Australia) — It was very interesting to learn of the development of a discomfort measuring instrument. I would like to ask Prof. KORSGAARD the following questions: How is the evaporative cooling effect considered in the instrument?

Is the resistance of clothing assured to be constant? Our own findings have shown that the impedence of clothing is a function of air velocity and can be taken a constant only in a narrow range of velocity, as used by ASHRAE, 30-40 ft/mn.

Have the predictions of the instrument been compared with field and laboratory experiments?

Is the instrument produced commercially, and if so, where could it be obtained?

V. KORSGAARD — 1. In the comfort zone the latent heat loss only depends upon the metabolism and the water vapour pressure.

$$\Phi_{wet} = f(p_a, \Phi_{total})$$

p_a and Φ_{total} are both set on the instrument, which then calculates Φ_{wet} according to the formula:

$$\Phi_{wet} = -6.9 + 0.518 \cdot \Phi_{total} - 0.0017\, \Phi_{total} \cdot p_a - 0.305 \cdot p_a (\mathrm{W/m^2}),$$

where p_a is measured in mbar.

2. The heat resistance of the clothing (clo-value) is set on the instrument and enters into the calculations with the set value. The apparatus does not take into account the variations of the clo-value for the actual air velocity around the feeler and among other things, because this correction is not known, it will be very much dependent on the type of the clothing (wind-proofness).

3. Yes, the instrument has been used together with the "thermal mannequin" for determination of thermal comfort in a hospital, and the values measured with the two instruments were in good agreement.

4. Yes, the instrument has been put into production at Reci A/S, Baldersgade 6, DK 2200 Copenhagen N, Denmark, and is expected to be ready for sale May/June 1972.

A. ADVANI (India) — Can this instrument detect the cause of discomfort?

V. KORSGAARD — Not directly, as the instrument measures the total thermal influence which the air temperature, the air velocity and the mean radiant temperature have on a person, and it is not possible with the instrument to separate the influence of the single parameters.

J. LEBRUN (Belgique) — Je pense que l'utilisation de telles sondes doit être très intéressante car elle permettra d'interpréter plus rationnellement les risques d'inconfort. Mais l'intérêt d'une sonde thermiquement active réside essentiellement dans la possibilité de déceler l'effet de l'agitation de l'air. A ce propos je trouve regrettable que la comparaison présentée par M. KORSGAARD à la figure 8 ne porte que sur le cas de l'air calme. Le problème qui nous préoccupe serait précisément de définir l'effet de la vitesse.

M. KORSGAARD a-t-il des indications à ce sujet : quels sont les coefficients d'échanges convectifs, et comment ces coefficients varient-ils en fonction de la vitesse?

Je pense qu'il serait intéressant pour tout le monde de savoir si de tels résultats sont disponibles et où ils sont publiés.

with the thermal mannequin at a constant air temperature, a constant mean radiant temperature and at air velocities between 0 and 0,84 m/s towards the front of the mannequin. By these measurements we have found the following connection between v and the ratio of m_u for $v = x$ m/s to m_u for $v = 0$ m/s, where m_u is the combined surface resistance.

It can be seen that the measured values of m_u as a function of v are considerably smaller than the values calculated from equation (V), whereas a good accordance is obtained if only the measured values on the part of the mannequin facing the air flow are taken into consideration.

Unfortunately it was impossible to determine Φ_R and Φ_C separately with these measurements.

We have just started examining the heat transfer between the thermal comfort feeler and the environment, and we will try to determine the influence of the single parameters t_a, L_{mrt} and v separately.

COMMENT

A.W. BOEKE (The Netherlands) — I could add to this, also as a reply on the last question of Mr. KOWALCZEWSKI, that I have seen this instrument being demonstrated at a similar meeting where all participants voted their appreciation of the climate in the room, according to the scale from -3 to $+3$. The value obtained, corresponds in fact almost exactly to the value shown by the instrument.

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