NEW INSTRUMENTS FOR MEASURING THERMAL COMFORT

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Nouveaux instruments de mesure du confort thermique

RÉSUMÉ : *On sait que le degré d'inconfort thermique ressenti par une personne est lié étroitement à la charge thermique que l'environnement impose à cette personne. Dans ce rapport, on définit la charge thermique comme la différence entre le métabolisme réel et le métabolisme correspondant à l'activité que la personne doit accomplir pour se trouver à l'état de confort thermique dans l'environnement réel. Ce dernier métabolisme peut être mesuré comme l'apport d'énergie à un corps de mesure qui doit conserver sa température superficielle à la même valeur que la température superficielle moyenne d'une personne à l'état de confort thermique avec une activité et des vêtements réels.*

Dans un environnement thermique non uniforme le confort thermique dépend aussi dans une certaine mesure, des écarts de la température de la peau pour les diverses parties du corps avec les températures correspondant au confort thermique.

Dans ce rapport on décrit deux instruments : un mannequin thermique et un compteur de confort thermique qui ont été mis au point au laboratoire de l'A. suivant les principes exposés ci-dessus.

INTRODUCTION

It is a well-known fact that the deep body temperature is kept almost constant at approx. 37 °C, even when the thermal variables of the environment vary within wide limits. But within these wide limits there is only a narrow interval or zone which will

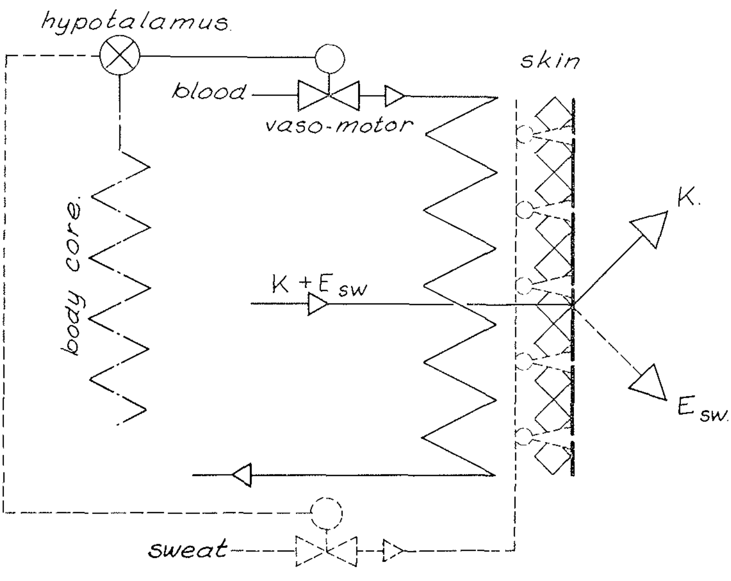

Fig. 1 — Physical thermoregulation.

activity and clothing. The body temperature is kept constant by means of the body's thermal effector mechanisms: vasodilation and vasoconstriction, sweat secretion and shivering (fig. 1).

The comfort zone can be referred 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 will mainly 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 thermoregulatory system as a simple proportional control system (fig. 2) we could claim 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.

$$\text{offset} = \text{actual value} \div \text{set point}.$$

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

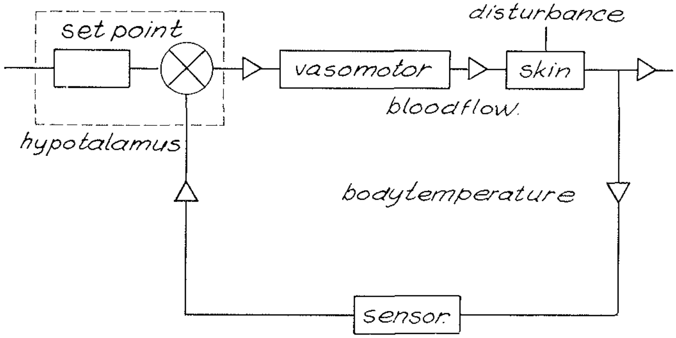

Fig. 2 — The human thermoregulating system within the comfort zone considered as a simple proportional control system.

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

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 factor of the control loop. The offset is given by the following expression:

$$\Delta T_b = \frac{k}{1+\alpha} \Delta H \tag{1}$$

From the equation it would be possible to find the amplification factor of the human thermoregulatory 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 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.

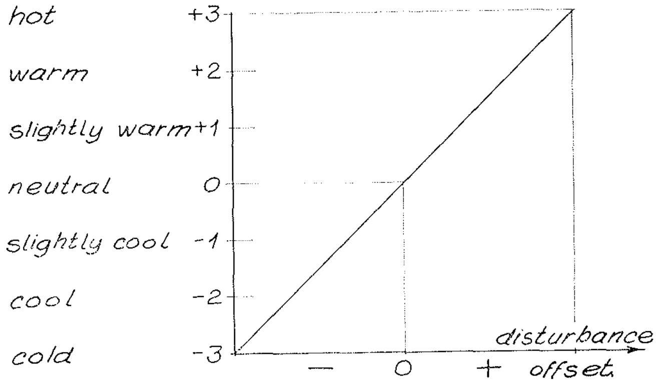

Fig. 3 — The degree of thermal discomfort as a function of the load error (disturbance).

Heat balance and disturbance

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

$$M \pm W = H = E_{ex} + E_{sw} + K \tag{2}$$

$$K = R + C \tag{3}$$

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:

$$\Delta H = H^a - (E_{ex} + E_{sw})^c - (R + C)^c \tag{4}$$

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

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

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

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

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 person in question.

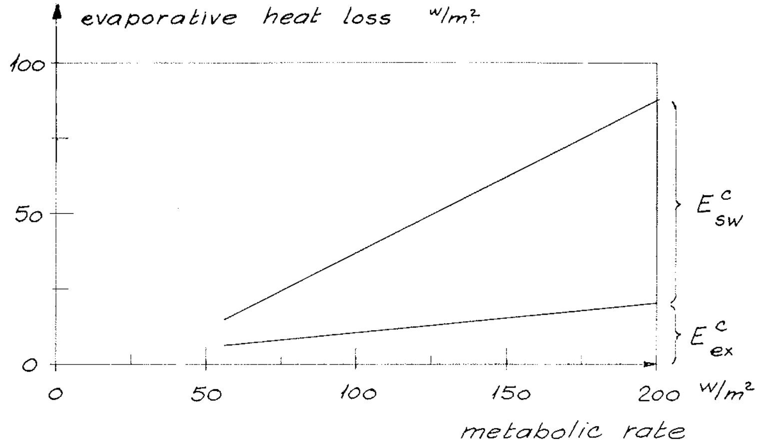

Fig. 4 — E^c_{ex} and E^c_{sw} as a function of the activity level (metabolic rate).

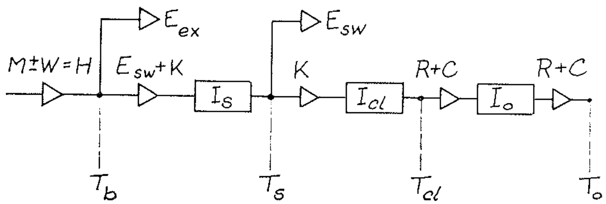

Fig. 5 — Blockdiagram of the body heat loss.

To calculate the combined heat loss $K^c = (R+C)^c$ 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 desired heat loss $(R+C)^c$. This problem must therefore be solved by iteration using the following formula:

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

where

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

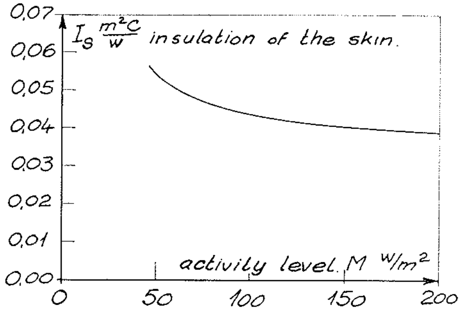

Fig. 6 — Insulation of the skin in the comfort condition as a function of the activity level.

level and can be found from figure 6. I_s^c 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_s^c can therefore also be taken directly from such measurements.

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 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 in somewhat more detail.

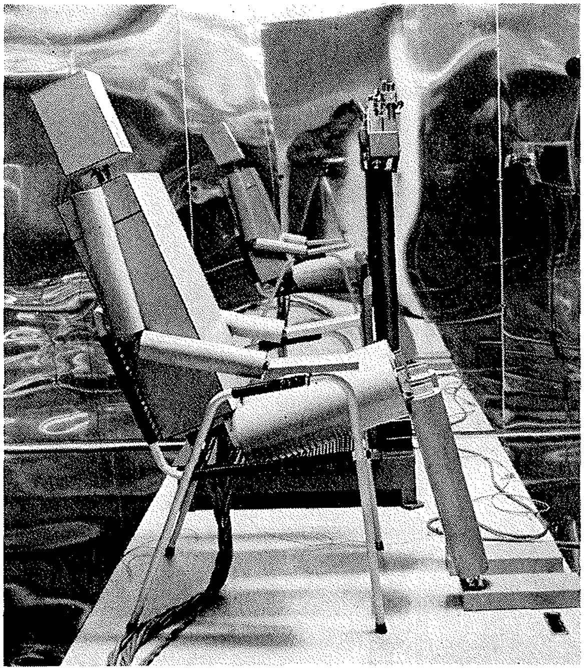

Fig. 7 — The thermal manikin in a climate room.

THERMAL MANIKIN

The instrument is shown in figure 7, [2]. As can be seen from the photo, the various parts of the body have been simplified in shape and are 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 having the same emissivity as the skin. The temperature difference across the insulation, which has a value equal to that of the skin I_s^c 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 is 37. This allows for 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 disturbance as defined earlier. The instrument is especially suitable in studies elucidating this problem, and also in the study of the thermal environment produced by various types of heating, cooling and ventilating systems.

THERMAL COMFORT METER

Although the manikin 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 (fig. 8), [3].

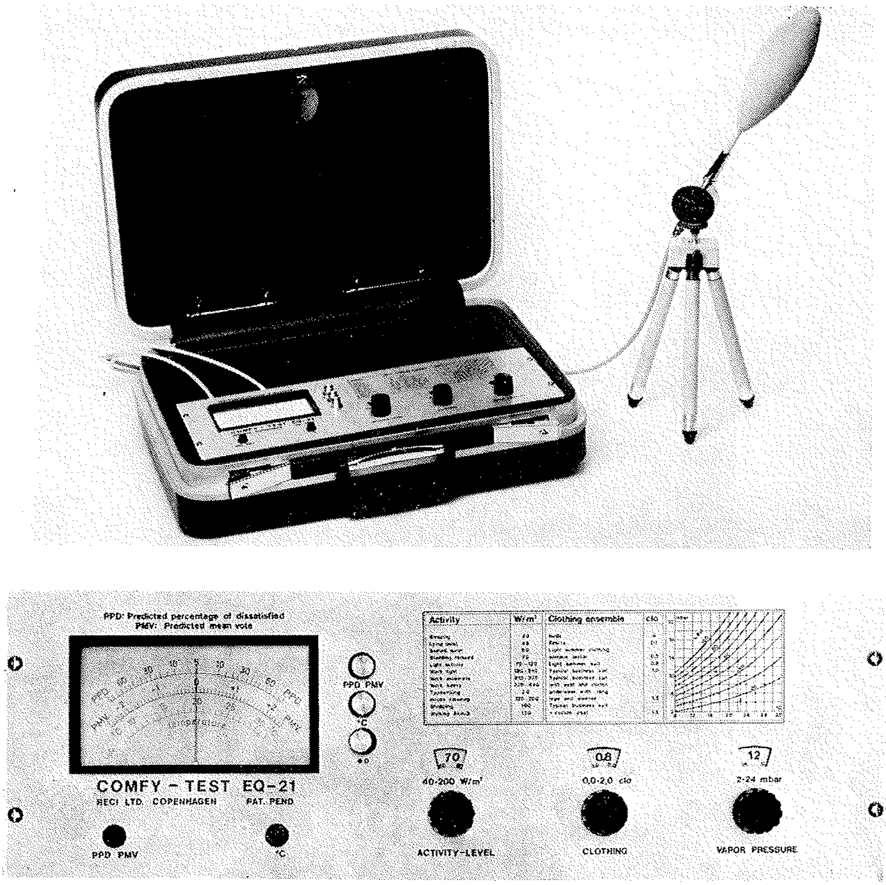

Fig. 8 — The thermal comfort meter.

THE SENSING BODY

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,

— position,
— 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 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 the body. On the other hand, the sensor's radiation- and convection-area are equal. This means that the sensor will emit 1/0.7 = 1.4 times as much heat per unit area by radiation as a person would at the same spot. However, it is propitious that a heated body's convective heat emittance per unit area becomes greater when the body becomes smaller. Therefore the main dimensions of the sensor are chosen so that its convective heat emittance per unit area is 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 unit area to the environment as a person would emit.

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 *position* 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 longwave 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 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.

THE CONTROLLING AND CALCULATING DEVICE

The control circuit for regulating the sensor's surface temperature 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

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

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

The instrument is shown on figure 8, where the dials for setting the activity level, the clo-value and the water vapour pressure can be seen. On the instrument scale the degree of thermal discomfort can be read either in numbers (PMV-value) corresponding to figure 3, or in percentage of thermally dissatisfied (PPD-value).

As 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.

Symbols

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

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