THERMAL COMFORT

by

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ABSTRACT

The theory and research behind the thermal comfort of a human being is described in this article. The parameters influencing the thermal comfort of an individual are incorporated in the comfort equation introduced by Prof. P.O. Fanger. Practical use of this equation is illustrated through the use of examples. The PMV and PPD indices are described, which quantify the degree of discomfort when the optimal thermal environment cannot be achieved. For practical measurements a Thermal Comfort Meter has been developed on which some of the parameters are dialled in, while the instrument measures the remaining parameters and computes in usable form a quantitative measure of comfort.

SOMMAIRE

La théorie et les recherches sur le confort thermique des êtres humains sont décrites dans cet article. Les paramètres influençant le confort thermique d'un individu sont introduits dans l'équation de confort établie par le Professeur P.O. Fanger. L'application pratique de cette équation est illustrée par des exemples. Les indices PMV et PPD, qui quantifient le degré d'inconfort lorsque l'ambiance thermique optimale n'est pas réalisée, y sont décrits. Pour les mesures pratiques, un Indicateur d'ambiance thermique a été conçu. Certains des paramètres sont introduits alors que les autres sont mesurés par l'appareil pour donner sous forme utilisable une mesure quantitative du confort.

ZUSSAMMENFASSUNG

In diesem Artikel ist die Theorie und Forschung über den Wärmekomfort (thermische Behaglichkeit) von Menschen beschrieben. Die Parameter, die den Wärmekomfort einer Person bestimmen, sind in der Komfort-Gleichung von Prof. P.O. Fanger enthalten. Die praktische Anwendung der Gleichung wird durch verschiedene Anwendungsbeispiele illustriert. Der PMV- und PPD-Index werden erläutert; mit ihnen erfolgt die Quantifizierung des Grads an Unbehagen, bei Nichterreichen optimaler thermischer Umgebungsbedingungen. Zur Durchführung von Messungen wurde das Wärmekomfort-Meßgerät entwickelt, welches drei manuell eingegebene Parameter sowie drei gemessene Parameter bei der Bestimmung des Wärmekomforts berücksichtigt.

Introduction

It has been known for a long time that the thermal comfort of a human being is not exclusively a function of air temperature, but also of five other, less obvious parameters; mean radiant temperature, relative air velocity, humidity, activity level, and clothing thermal resistance. However, the combined quantitative influence of all the parameters was not known until the "Comfort Equation" established by Prof. P.O. Fanger [2] was introduced. When any combination of these parameters satisfies this equation, the thermal comfort of a majority of individuals can be stated to be neutral.

Before discussing the thermal comfort equation, the thermo-regulatory system of the human being will be described, as well as the above mentioned parameters influencing the heat balance of an individual. For the practical application of the comfort equation, use has to be made of comfort diagrams, which are curves of various combinations of two parameters which will create comfort, provided the other parameters are kept constant. Use of these diagrams are illustrated through various examples.

In practice it is not always feasible (technically or economically) to provide optimal thermal comfort. In this case it is often of value to quantify the degree of discomfort, for which purpose the PMV (Predicted Mean Vote) index has been devised on the basis of tests conducted on a group of more than 1300 subjects. Once the PMV value has been established from tables, it is then possible to determine the PPD (Predicted Percentage of Dissatisfied) index.

Determination of thermal comfort, PMV and PPD indices are rather time consuming procedures using graphs and tables. A "Thermal Comfort Meter", Type 1212, has therefore been developed where three parameters, clothing, activity and vapour pressure are dialled in, while the instrument measures the combined effect of the other three parameters, and computes in usable form a quantitative measure of comfort.

Thermo-regulatory System of a Human Being

A human being has a nearly constant internal temperature ~37°C, and is not influenced even by large variations in ambient temperature. The internal temperature (core-temperature) can be kept constant only if there is balance between the heat which is produced by the body and the heat which is lost to the envriornment. In warm-blooded mammals, including man, the heat balance is controlled mainly by the hypothalmus, which is the part of the brain that acts like a thermostat.

The heat balance is controlled by the information the temperature centre receives about the temperature conditions in the body. Thermoreceptors are situated both in the temperature centre in the brain and to a great extent in the skin. There are probably also thermo-receptors in other parts of the body as muscles, lungs and spinal-cord. There are both cold receptors and warm receptors. When the temperature, especially temperature changes, influence these receptors, nerve impulses are transmitted to the temperature centre in the brain. Here the information is co-ordinated, resulting in reactions which will keep the internal body temperature constant.

Cold receptors start cold sensations if the temperature in a skin area decreases faster than approximately 0,004°C/s (14,4°C/h). Warm receptors start warm-sensations if the temperature in a skin area increases faster than approximately 0,001°C/s (3,6°C/h).

The heat production in the body takes place continuously by the metabolic process which converts chemical energy into heat. This heat production (basal-metabolism) is of the order 1 W/kg (body weight), if it is measured at rest during certain standard conditions (fasting 8 hours after last meal, and lying relaxed at a neutral temperature). In cold environments the temperature centre starts tensions in the muscles, which start the metabolic process, and heat production increases. In still colder environments, the muscle tensions will cause shivering, which can increase the heat production by a factor of three times the basal metabolism.

The greatest changes in heat production are, however, the result of muscle work, which can change the heat production by a factor of 10 times the basal metabolism.

The heat is transported from the warm core to the skin partly by conduction through the tissues and partly by blood flow to the skin.

In cold environments the nerve impulses from the cold receptors result in vaso-constriction i.e. contraction of the blood vessels, decreasing the blood flow and thus heat flow to the skin. To maintain a high temperature (37°C) in the vital parts of the body, the blood flow is reduced first to the extremities (hands and feet), where the cold sensation is first experienced. When all blood vessels in the skin are completely closed, there will still be heat loss by conduction through the skin to the environment. This heat loss is dependent on the thermal insulation of the skin, which is in the range 0,1 to 1,0 clo depending on the thickness of the layer of fat.

In a hot environment the temperature of the skin is high, and the temperature gradient between the body core and the skin surface is small. Heat exchange by conduction from the core to the skin surface is therefore small. In warm environments however, the blood flow is increased due to vaso-dilation — opening of the blood vessels. For the skin as a whole the blood flow can increase as much as 10 times the minimum. The heat then produced is transported by the blood to the skin surface, where in hot environments it is lost mainly by evaporation of sweat. In hands and feet the blood flow may be changed by a factor of 30.

The regulation of heat loss by evaporation is achieved by secretion of water from the sweat glands. Uncontrolled evaporation of water diffused through the skin (perspiration insensibili) takes place continuously. Furthermore the water content of the air that we inhale is less than that of the air we exhale. But the amount due to the evaporation when breathing is however minimal, approximately 40 g/h, equivalent to a heat loss of approximately 28 W. The sweat glands can produce up to 2 to 3 litres of water per hour. Each gram or ml. which evaporates will remove 2,43 kJ from the skin surface. The sweat production, like the blood flow in the skin, is mainly controlled by the temperature centre in the hypothalmus.

Core Temperature and Skin Temperature

The above-mentioned thermo-regulation possibilities, i.e., in cold conditions decreased blood flow and shivering (increased metabolism), and in hot conditions increased blood flow and evaporation of sweat, attempt to maintain a core temperature within certain limits. The core temperature may change from approximately 36°C to 40 – 42°C, under certain circumstances, while the variation in mean skin temperature can be much greater, 17° to 40°C.

The normal core temperature in rest measured in the morning is approximately 37°C. However, there are significant individual differences (36° to 38°C). During a day the core temperature will normally vary by approximately 1°C. The temperature increases during the day and reach its maximum value late in the afternoon. Then it drops again and reaches the lowest temperature during the morning.

During muscle work the body temperature will increase to a higher level, depending on the amount of work. It is now generally believed that this increase is made to benefit the rate of the metabolic process in the working muscles. The core temperature is kept constant independent of great variation in the environmental conditions. But as the body's capacity for heat production and sweat production is limited, there exist upper and lower limits for keeping the heat balance.

If the ambient temperature rises above the upper limit for the regulation area, heat will be accummulated in the body and the core temperature will increase. Then the heat exchange between core and skin surface increases due to the increased blood flow and a new heat balance may be reached, but at a higher level of core temperature. If the environment is too hot the internal temperature will keep increasing up to a fatal level of 42° to 43°C.

In cold environments, where the heat loss even with maximum vasoconstriction is greater than the heat production, the core temperature will decrease. The first reaction is that shivering will start but at approximately 33°C shivering stops and at lower temperatures one reaches unconsciousness. A body temperature of approximately 25°C is fatal.

The skin temperature at different parts of the body tend to be uniform in hot environments. But in cold environments hands, feet, legs and arms in particular, become relatively colder than the head and torso (see Fig.1). The pain limit occurs at approximately 45°C skin temperature.

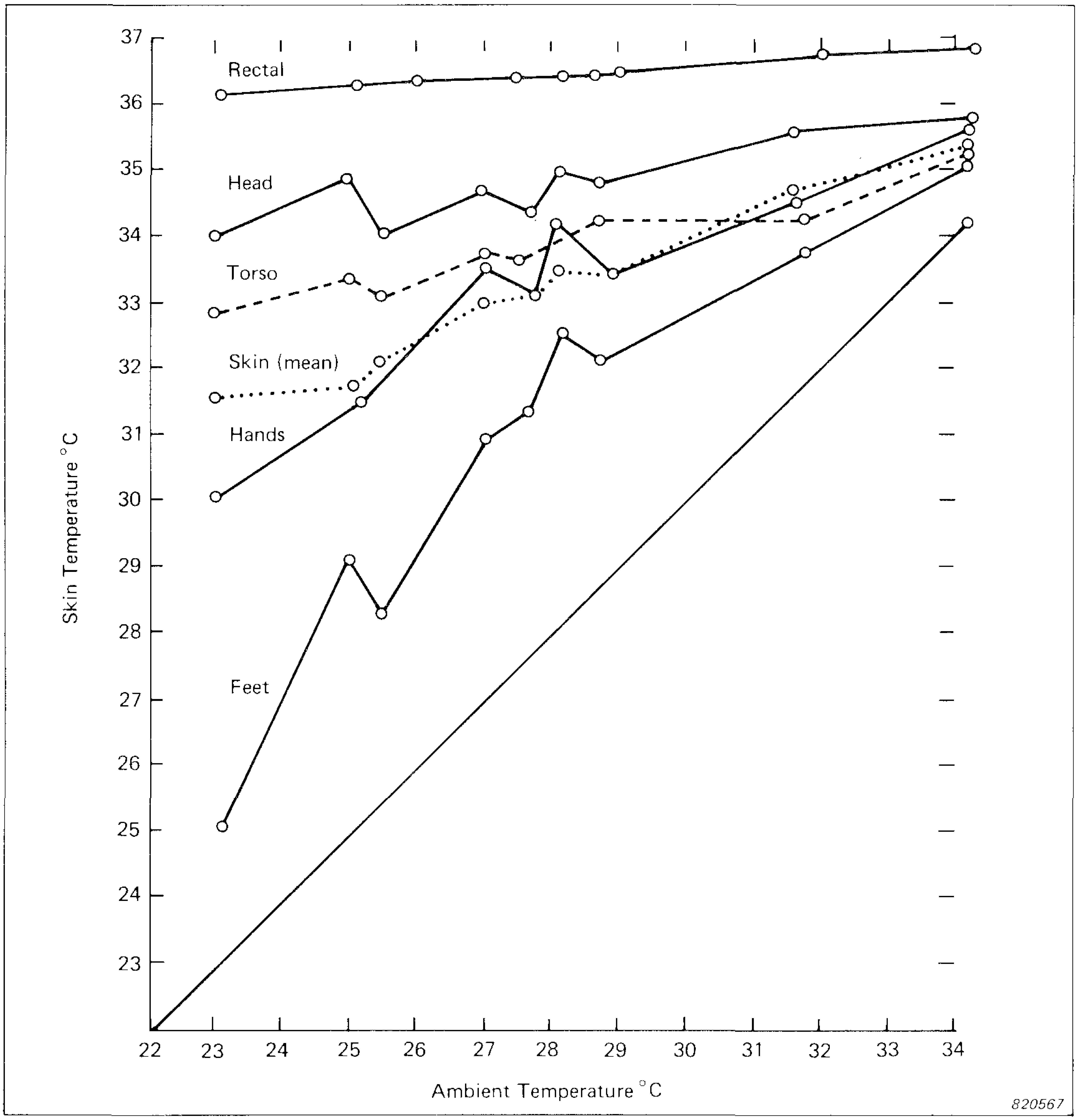

Fig. 1 Skin temperatures on different parts of a nude person measured at different ambient temperatures

Man's Heat Balance

This section discusses the different ways a human being can lose or gain heat from the environment. As mentioned earlier the body's core temperature remains constant on the condition that there is balance between the heat production and the heat loss.

Heat balance:

$$S = M \pm W \pm R \pm C \pm K - E - RES \qquad (1)$$

where S = Heat storage
M = Metabolism
W = External work
R = Heat exchange by radiation
C = Heat exchange by convection
K = Heat exchange by conduction
E = Heat loss by evaporation
RES = Heat exchange by respiration

Heat balance is reached if the storage $S = 0$.

The above heat balance equation is often used. However, when dealing with a person with clothing it is preferable to write the heat balance equation as ($S = 0$):

$$M \pm W - E - RES = \pm K_{cl} = \pm R \pm C \qquad (2)$$

where K_{cl} = Heat conduction through the clothing

The sign indicates that the parameter may be negative or positive i.e. heat loss or heat gain.

The double equation implies, that the metabolism *(M)* including the external work *(W)* minus the heat loss by evaporation *(E)* and respiration *(RES)* is equal to the heat conduction through the clothing (K_{cl}) and equal to the heat loss by radiation *(R)* and convection *(C)* from the outer surface of the clothing.

The above equation does not take into account the heat exchange by conduction, for example, when loading sacks or the contact between feet and the floor. This amount is normally insignificant compared to the total heat exchange, but has of course a significant influence on local heat exchange (warm fingers, cold toes).

A person seated in an armchair, will exchange heat by conduction to the chair across a substantial surface area. In this case the chair should be calculated as part of the clothing.

Metabolism, *M*

Energy is released in the body by oxidation. This takes place at a rate which is equivalent to the amount of energy the body needs to function. The value of M may vary from a rest value of approximately 45 W/m^2

skin surface (0,8 met) to more than 500 W/m^2 ($\sim$ 9 met) when running. The surface area of a normal person is approximately 1,8 m^2. The energy released is sometimes partly converted to external mechanical power *W* but is mainly converted into internal body heat. The metabolism is often given in the unit "met", where 1 met is equal to the metabolism for a seated, resting person (1 met = 58,15 W/m^2). In Table 1 a list of activities and their corresponding met values are given.

ACTIVITY	met	W/m^2
Lying down	0,8	47
Seated, quietly	1,0	58
Sedentary activity (office, home, laboratory, school)	1,2	70
Standing, relaxed	1,2	70
Light activity, standing (shopping, laboratory, light industry)	1,6	93
Medium activity, standing (shop assistant, domestic work, machine work)	2,0	117
High activity (heavy machine work, garage work)	3,0	175

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Table 1. Examples of metabolic rate M for various practical activities

It is seen that a seated person produces heat equivalent to two 60 W bulbs. Increased metabolism will in most cases result in an increase in relative air velocity due to body movements [25]. This effect is not fully studied yet and more research is needed to evaluate it.

External Work, *W*

W can be both positive or negative. If a person cycles on an ergometer with a heavy load, he must use a lot of energy to keep a constant velocity (r/min). This energy is split in two parts: *W* is the amount which is necessary to overcome the resistance from the load. In this case *W* is positive. The other part is the internal heat production, which is necessary for the body to perform external work equal to *W*. This part of the energy is used to pump more blood around and increase the respiration.

Man is, however, a very poor machine. The efficiency is less than 20% even for well-trained athletes. Thus if the load on the ergometer is increased such that the corresponding *W* is increased by 10 W/m^2, then the metabolism will increase by 50 W/m^2. The extra 40 W/m^2 must then normally be lost by increased sweating to avoid increment of the internal temperature.

If one walks down a steep hill and has to "brake" not to get too much speed, some of the potential energy will be transformed to heat in the muscles. The external work, W, is in this case negative. The external work can also be lifting a tool, sack or case and then increase the potential energy for this object.

Heat Loss by Evaporation *E*

Heat loss by evaporation is partly from water vapour diffusion through the skin (E_d) and partly by evaporation of sweat on the skin surface (E_{SW}). When evaporation takes place the water uses heat from the skin.

The amount of water diffusion through the skin and the corresponding evaporative heat loss (E_d) is a function of the difference between the saturated water vapour pressure at skin temperature (p_s) and the water vapour pressure in the ambient air (p_a).

$$E_d = 3{,}05 \cdot 10^{-3} \, (p_s - p_a) \qquad \mathrm{W/m^2} \tag{3}$$

where p_s and p_a are in Pa (Pascal)

The saturated water vapour pressure at the skin surface is a function of the skin temperature (t_s):

$$p_s = 256 \, t_s - 3373 \qquad \text{Pa (Pascal)} \tag{4}$$

Inserting (4) in (3) we obtain

$$E_d = 3{,}05 \cdot 10^{-3} \, (256 \, t_s - 3373 - p_a) \qquad \mathrm{W/m^2} \tag{5}$$

Water diffusion through the skin will normally result in a heat loss equal to approximately 10 W/m^2. A typical case is skin temperature t_s = 33°C and a water vapour pressure p_a = 1400 Pa in ambient air (50% relative humidity at 23°C air temperature). This will result in a heat loss equal to 11,2 W/m^2.

The heat loss by water diffusion through the skin takes place all the time and is not controlled by the thermo-regulatory system.

Evaporation of sweat from the skin surface *(E_{sw})* is one of the most effective ways by which the body can keep the internal temperature from increasing even during hard work. The amount of this evaporation may change a lot with activity (from 0 W/m^2 at rest to maximum 400 W/m^2 with very hard work) in a hot, dry environment.

It is limited how much a person is able to sweat and there are great individual differences. Persons who are used to living and working in hot environments or performing hard work can improve the function of the sweat glands and obtain a better control of the body temperature. An acclimatised person is normally not able to sweat more than 1 l per hour, and a total amount of approximately 3,5 l. If all this sweat is evaporated, it is equal to a heat loss of 675 W (375 W/m^2) and a total amount of 8505 kJ.

During hard work in hot environments it is important to drink water (plus salt) to be able to sweat enough. The estimation of the heat loss due to the evaporation of sweat is rather complicated and not fully understood yet. By excessive sweating some of the produced sweat will drip and does not remove any heat from the body by evaporation. It is only the sweat which evaporates at the skin surface that removes heat from the body.

A typical example of the influence of evaporation is experienced in a sauna. Here the ambient temperature is around 100°C and it is then possible to lose heat only by evaporation of sweat from the skin. As the air in a sauna is dry it is possible to evaporate enough to avoid any dangerous increase in the internal temperature. If one pours water on the hot stove in the sauna, the humidity will increase and a sudden heat discomfort is experienced due to the decrease in evaporation and at the same time increase sweating.

At moderate activities (in office work, residential buildings, light industry) the evaporation is of less significance and takes account of approximately 25% of the total heat loss. For moderate sweat secretion and air temperature, and thus moderate vapour pressures, which apply to persons in a state of thermal comfort, it would seem reasonable to assume that all secreted sweat evaporates. The significance and the estimation of the evaporation from the skin *(E_{sw})* will be dealt with later when discussing the conditions for thermal comfort.

Heat Loss by Respiration, *RES*

When breathing heat is lost because the exhaled air is warmer than the inhaled air and because there are differences in the water content. The heat exchange due to the difference in temperature is given by

$$L = 0{,}0014\, M\, (34 - t_a) \qquad \mathrm{W/m^2} \tag{6}$$

where M = metabolism, $\mathrm{W/m^2}$
t_a = ambient air temperature, °C

The temperature of the expired air is assumed to be 34°C. This loss is normally insignificant. A running person (M ~ 400 $\mathrm{W/m^2}$ ~ 7 met) at an air temperature –10°C will loose 44 W (25 $\mathrm{W/m^2}$).

The heat loss due to the differences in water vapour between inhaled and exhaled air is estimated by:

$$E_{res} = 1{,}72 \cdot 10^{-5}\, M\, (5867 - p_a) \qquad \mathrm{W/m^2} \tag{7}$$

where p_a = water vapour pressure in ambient air, Pa.

The heat loss for the same example as above at a vapour pressure of 600 Pa (50% RH) will be 65 W (36 $\mathrm{W/m^2}$).

For normal indoor activities (seated/standing) and ambient temperatures around 20°C the heat losses by respiration are small, less than 2 to 5 $\mathrm{W/m^2}$, and may often be neglected.

Heat Conduction through the Clothing, K_{cl}

The heat exchange through the clothing is given by:

$$K_{cl} = (t_s - t_{cl})\, /\, 0{,}155\, I_{cl} \qquad \mathrm{W/m^2} \tag{8}$$

where t_s = mean skin temperature, °C
t_{cl} = clothing surface temperature, °C
I_{cl} = thermal insulation of the clothing, clo

In Table 2 the thermal insulation are shown for some typical clothing combinations. The estimation of t_s and t_{cl} is dealt with later.

CLOTHING COMBINATION	clo	m^2K/W
Naked	0	0
Shorts	0,1	0,016
Typical tropical clothing outfit *Briefs (underpants), shorts, open-neck shirt with short sleeves, light socks, and sandals*	0,3	0,047
Light summer clothing *Briefs, long light-weight trousers, open-neck shirt with short sleeves, light socks, and shoes*	0,5	0,078
Working clothes *Underwear, cotton working shirt with long sleeves, working trousers, woollen socks, and shoes*	0,8	0,124
Typical indoor winter clothing combination *Underwear, shirt with long sleeves, trousers, sweater with long sleeves, heavy socks, and shoes*	1,0	0,155
Heavy traditional European business suit *Cotton underwear with long legs and sleeves, shirt, suit comprising trousers, jacket and waistcoat (US vest), woollen socks, and heavy shoes*	1,5	0,233

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Table 2. Examples of values of I_{cl} for various practical combinations of clothing

It is assumed that all the evaporation which takes place at the skin surface will be transported through the clothing by diffusion. It is acceptable in most cases as the resistance to diffusion in normal clothing is very small and in the comfort zone the sweat production is also minimal. When the activity is increased the effective clothing insulation will often decrease due to the "pumping" effect, i.e., increased air exchange between clothing and skin. This effect has been studied only in very few cases [12, 13] and more research is needed on this subject.

Heat Exchange by Radiation, *R*

The heat exchange by radiation takes place between the surface of the person (skin-clothing) and the surrounding surfaces (windows, walls, heaters). The heat exchange is estimated by the following equation:

$$R = f_{eff}\ f_{cl}\ \epsilon\ \sigma \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right] \ \mathrm{W/m^2} \qquad (9)$$

where f_{eff} = the effective radiation area factor, i.e. the ratio of the effective radiation area of the clothed body to the surface area of the clothed body

f_{cl} = clothing area factor, i.e. the ratio of the surface area of the clothed body to the surface area of the nude body

ϵ = the emittance of the outer surface of the clothed body

σ = the Stefan-Boltzmann constant: $5{,}77 \cdot 10^{-8}$ W/m^{2}K^4

t_{cl} = the clothing surface temperature, °C

$\bar{t}_r$ = the mean radiant temperature, °C

In all the previous equations the heat loss from a person is given as W/m^2 of skin surface area of a nude person. But as the heat exchange by radiation takes place at the clothing surface area (which is always greater than the nude surface area), it is necessary to multiply by the factor f_{cl}.

Some parts of the clothing surface exchange heat by radiation not with the environment, but with other parts of the body, i.e. between arms and body, and between the legs. The effective radiant area is then less than the total surface area. This effect is included in the factor, f_{eff}. The value of f_{eff} is found by experiments to be 0,696 for seated persons and 0,725 for standing. As the difference is relatively small, a mean value equal to 0,71 is used.

Since the emittance for human skin is close to 1,0 and most types of clothing have emittance of about 0,95 a mean value of 0,97 is used. Emittance, ϵ, for skin and clothing is independent of the colour for low temperature radiation, which normally is the case indoors. For short wave radiation, as sunlight, the emittance is influenced by the colour.

The mean radiant temperature $\bar{t}_r$ is defined as the uniform temperature of the surrounding surfaces, which will result in the same heat exchange by radiation from a person as in the actual environment. The mean radiant temperature is estimated from the temperature of the surrounding surfaces weighted according to their relative influence on a person by the angle factor

$$\bar{t}_r = \sqrt[4]{F_{p-1}(t_1 + 273)^4 + F_{p-2}(t_2 + 273)^4 + \ldots + F_{p-n}(t_n + 273)^4} - 273 \quad (10)$$

where t_n = temperature of surface n, °C
F_{p-n} = angle factor between person and surface n
$\Sigma F_{p-n} = 1$

The mean radiant temperature is then dependent on both a person's posture and his position in a room.

When the above constants are inserted the radiant heat loss is given by:

$$R = 3{,}95 \cdot 10^{-8}\ f_{cl} \left[(t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right] \quad \mathrm{W/m^2} \qquad (11)$$

For the normal indoor temperature range (10° to 30°C) this equation may be written as a linear equation:

$$R = 3{,}9\ f_{cl}\ (t_{cl} - \bar{t}_r) \qquad \mathrm{W/m^2} \qquad (12)$$

If the mean radiant temperature is higher than the surface temperature of a person, there is heat gain by radiation. This is often the case in the steel and glass industry owing to the hot metal or the radiation from a furnace.

Heat Exchange by Convection, *C*

A person's surface temperature differs normally from the ambient air temperature. The air close to the person will be heated and since heated air has lower mass than cold air it will move upwards and colder air will move towards the surface of the person. This heat loss is named *free convection.*

If the air is forced towards a person (by a fan, draught) it is called *forced convection.*

The heat exchange by convection is given by:

$$C = f_{cl}\ h_c\ (t_{cl} - t_a) \qquad \mathrm{W/m^2} \qquad (13)$$

where t_a = air temperature, °C
f_{cl} = clothing area factor
h_c = convective heat transfer coefficient $W/m^2 K$

For free convection, h_c depends on the temperature difference between clothing, t_{cl} and air, t_a:

$$h_c = 2{,}38\ (t_{cl} - t_a)^{0{,}25} \quad W/m^2 K \tag{14}$$

For forced convection, h_c depends on the relative air velocity:

$$h_c = 12{,}1\ \sqrt{v_{ar}} \quad W/m^2 K \tag{15}$$

In each individual case it is necessary to evaluate if free or forced convection is the most significant. In most cases free convection is valid when $v_{ar} < 0{,}1$ m/s. It is important to emphasize that it is the relative air velocity which has to be used. When a person walks or performs an activity where he moves arms and/or legs, the increased relative air velocity increases the convective heat loss coefficient h_c.

Conditions for Thermal Comfort

Thermal comfort is defined as that state of mind in which satisfaction is expressed with the thermal environment.

The first condition for thermal comfort is that the heat balance equation (2), described in the previous section, is fulfilled.

At a given level of activity *(M)*, mean skin temperature *(t_s)* and sweat loss *(E_{sw})* are the only physiological parameters which influence the heat balance. For a given person at a given activity, clothing and environment, the heat balance will be established by a certain combination of mean skin temperature and sweat loss.

Heat balance is, however, not sufficient to establish thermal comfort. In the wide range of environmental conditions where heat balance can be obtained, there is only a narrow range which will provide thermal comfort. This range is then related to a narrow range for both mean skin temperature and sweat loss. It is assumed that for each individual and at a given activity, there is a range of values of mean skin temperature *(t_s)* and sweat loss *(E_{sw})* which will provide thermal comfort.

$$a < t_s < b \tag{16}$$

$$c < E_{sw} < d \tag{17}$$

These limits will vary with activity and individuals.

In tests with subjects in states of thermal comfort, relations between activity and mean skin temperature, and between activity and sweat loss, were established as shown in Fig.2 and Fig.3. From these Figures the individual differences are obvious and a mean value is used when establishing the comfort equation.

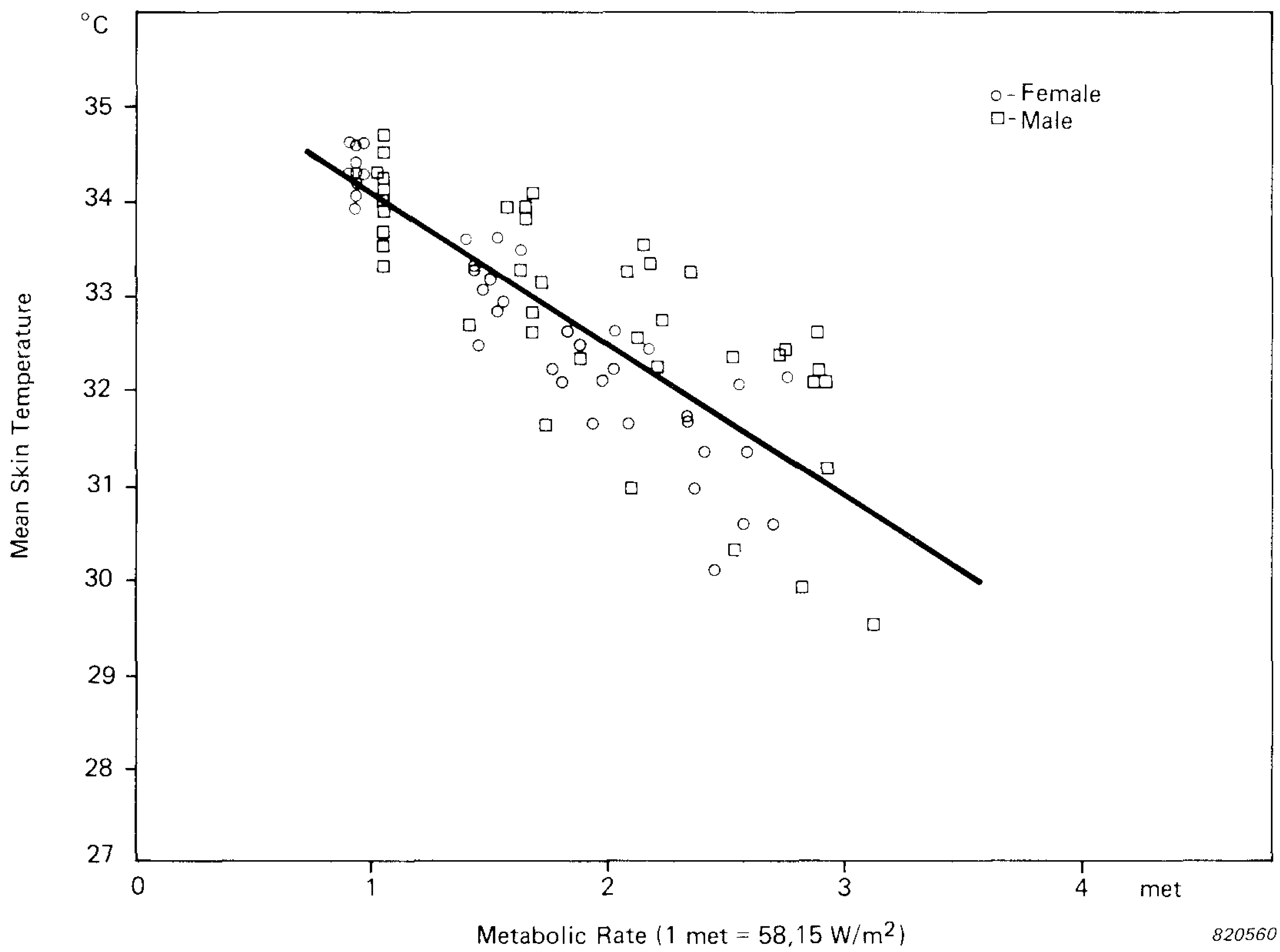


Fig. 2 Mean skin temperature as a function of the activity level for persons in thermal comfort. In order to maintain thermal comfort the ambient temperature is lower the higher the activity level [2]

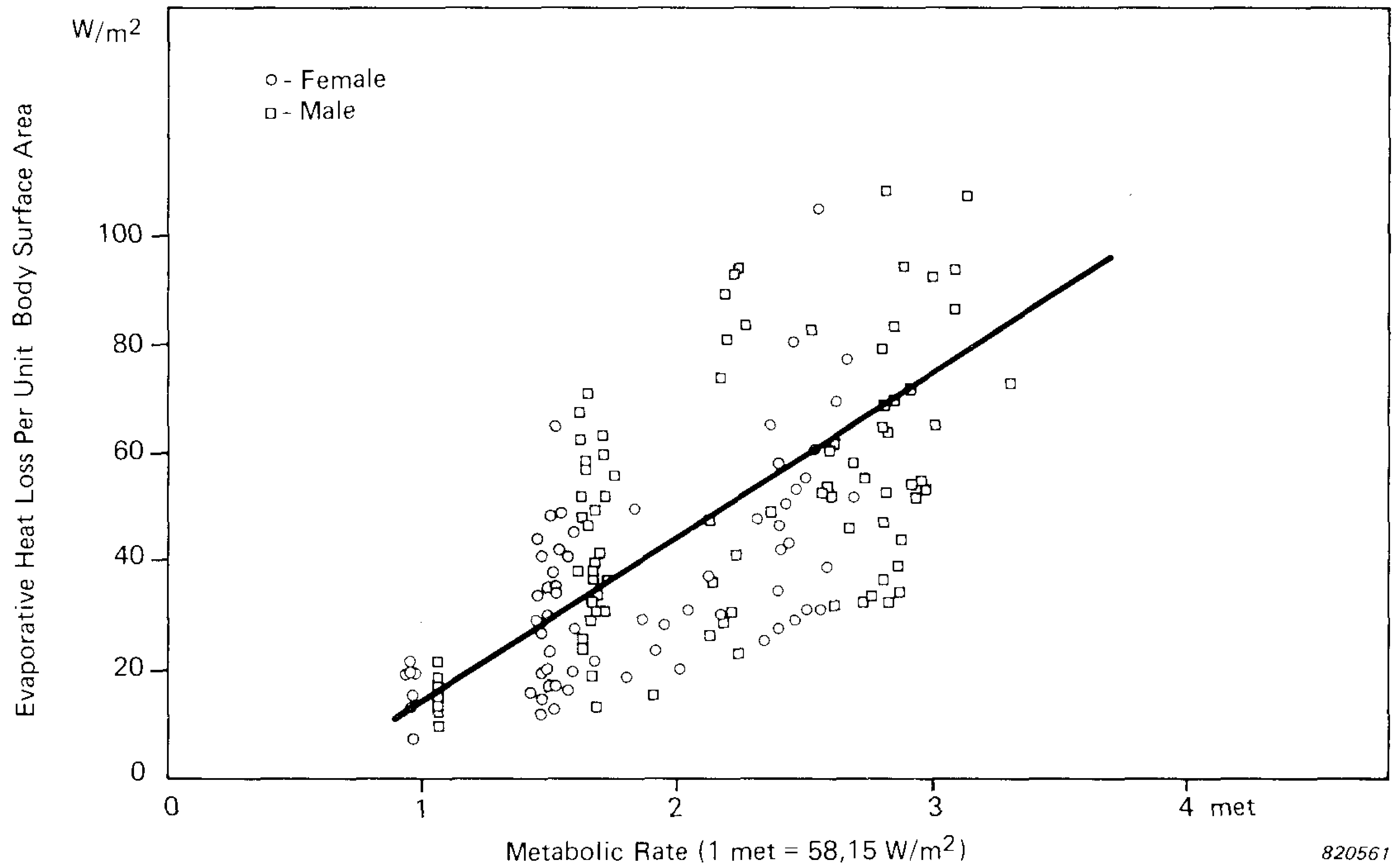


Fig. 3. Evaporative heat loss as a function of the activity level for persons in thermal comfort. In order to maintain thermal comfort the ambient temperature is lower the higher the activity level [2]

Using linear regression the following relations are found:

$$t_s = 35{,}7 - 0{,}0275\,(M - W)\ ^\circ\mathrm{C} \qquad (18)$$

$$E_{sw} = 0{,}42\ (M - W - 58{,}15) \qquad \mathrm{W/m^2} \qquad (19)$$

The mean skin temperature decreases at higher activities and the sweat loss increases. Both reactions will increase the heat loss from the body core to the environment. For a person seated quietly (M = 58 W/m^2, W = 0) in a state of thermal comfort the mean skin temperature is 34,1°C and there is no sweat loss. But there is still evaporative heat loss from water vapour diffusion through the skin and respiration.

The Comfort Equation

If the equations for the heat loss derived in the previous section and the two equations for t_s and E_{sw} are inserted in the double sided heat balance equation (2) the comfort equation is established:

$$(M-W) - 3{,}05 \cdot 10^{-3} \left\{ 5733 - 6{,}99\,(M-W) - p_a \right\}$$

$$- 0{,}42 \left\{ (M-W) - 58{,}15 \right\} - 1{,}7 \cdot 10^{-5}\, M\,(5867 - p_a) - 0{,}0014\, M\,(34 - t_a)$$

$$= 3{,}96 \cdot 10^{-8}\, f_{cl} \left\{ (t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \right\} - f_{cl}\, h_c\,(t_{cl} - t_a) \qquad (20)$$

where $t_{cl} = 35{,}7 - 0{,}028\,(M-W) - 0{,}155\, I_{cl} \Big[(M-W)$

$$- 3{,}05 \cdot 10^{-3} \left\{ 5733 - 6{,}99\,(M-W) - p_a \right\} - 0{,}42 \left\{ (M-W) - 58{,}15 \right\}$$

$$- 1{,}7 \cdot 10^{-5}\, M\,(5867 - p_a) - 0{,}0014\, M\,(34 - t_a) \Big]$$

$$h_c = \begin{cases} 2{,}38\,(t_{cl} - t_a)^{0{,}25} & \text{for } 2{,}38\,(t_{cl} - t_a)^{0{,}25} > 12{,}1\sqrt{v_{ar}} \\ 12{,}1\sqrt{v_{ar}} & \text{for } 2{,}38\,(t_{cl} - t_a)^{0{,}25} < 12{,}1\sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1{,}00 + 0{,}2\, I_{cl} \text{ for } I_{cl} < 0{,}5 \text{ clo} \\ 1{,}05 + 0{,}1\, I_{cl} \text{ for } I_{cl} > 0{,}5 \text{ clo} \end{cases}$$

The Comfort Equation establishes those combinations of activity, clothing, and the four environmental variables (air temp., mean radiant temp., air velocity, humidity) which will provide thermal comfort. It has been known for a long time that these six variables influence the state of comfort. But the combined quantitative influence of all the parameters on man's comfort was not known until the Equation was introduced.

Practical Application of the Comfort Equation

The Comfort Equation is comprehensive and complex and therefore unsuitable for manual calculation, but it has been solved by the use of an electronic computer and has been plotted in 28 comfort diagrams [2]; these diagrams are intended for use in practice. In Figs.4 to 8 examples are shown of the comfort diagrams. In each diagram, comfort lines have been drawn, i.e. curves through various combinations of two variables which will create comfort providing the values of the other variables are kept constant.

For practical application of the comfort diagrams, it is necessary to estimate the activity level and the clothing first, taking into account the use of the room (see Tables 1 and 2). From the comfort diagrams, combinations can then be found of the four environmental parameters which will provide thermal comfort.

Several characteristic examples are given below of the use of the comfort diagrams in practice.

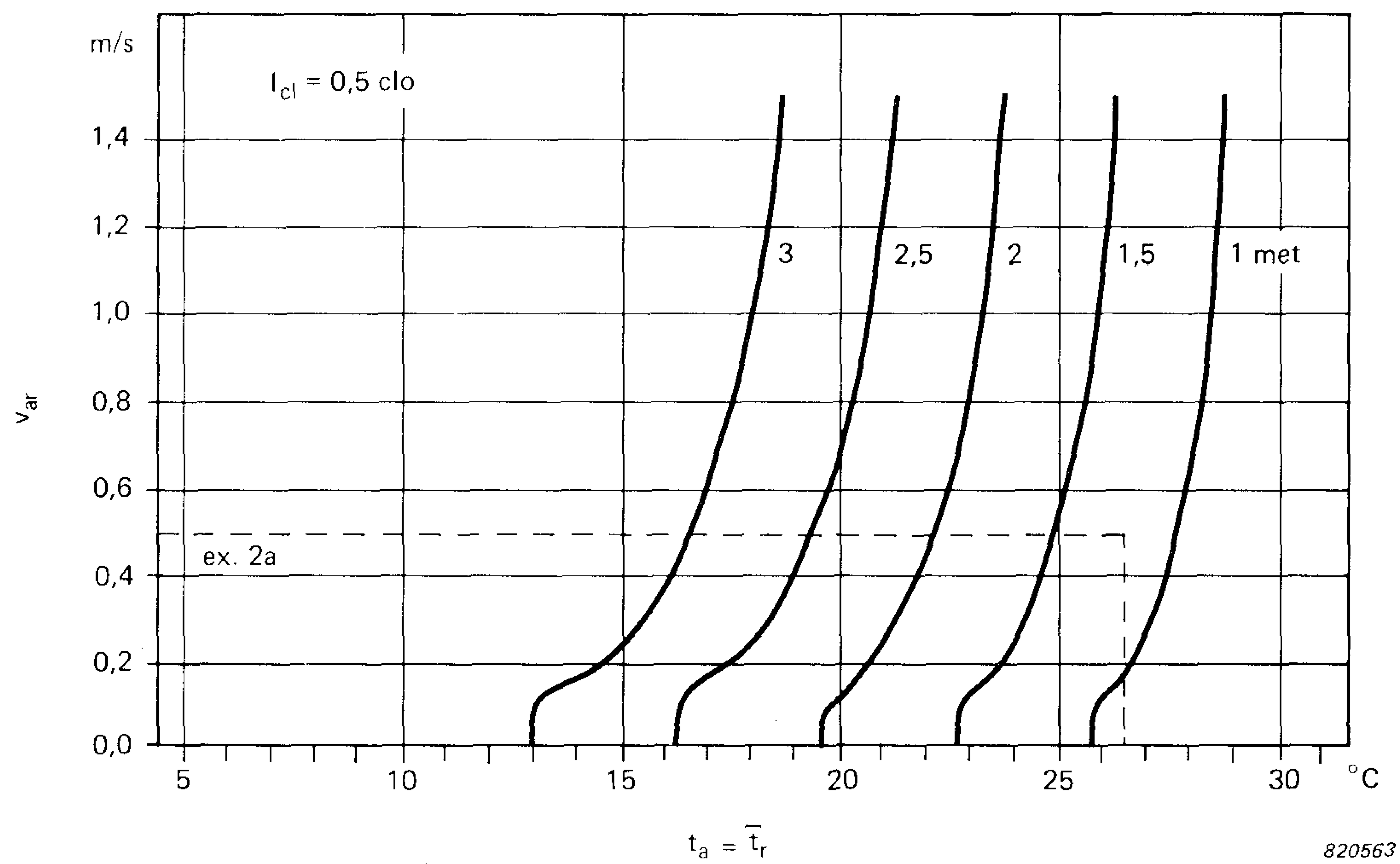


Fig. 4. Comfort lines for 0,5 clo and Relative Humidity 50%. Relative Velocity v_{ar} as a function of air temperature t_a = mean radiant temperature, $\bar{t}_r$ for various activity M as parameter

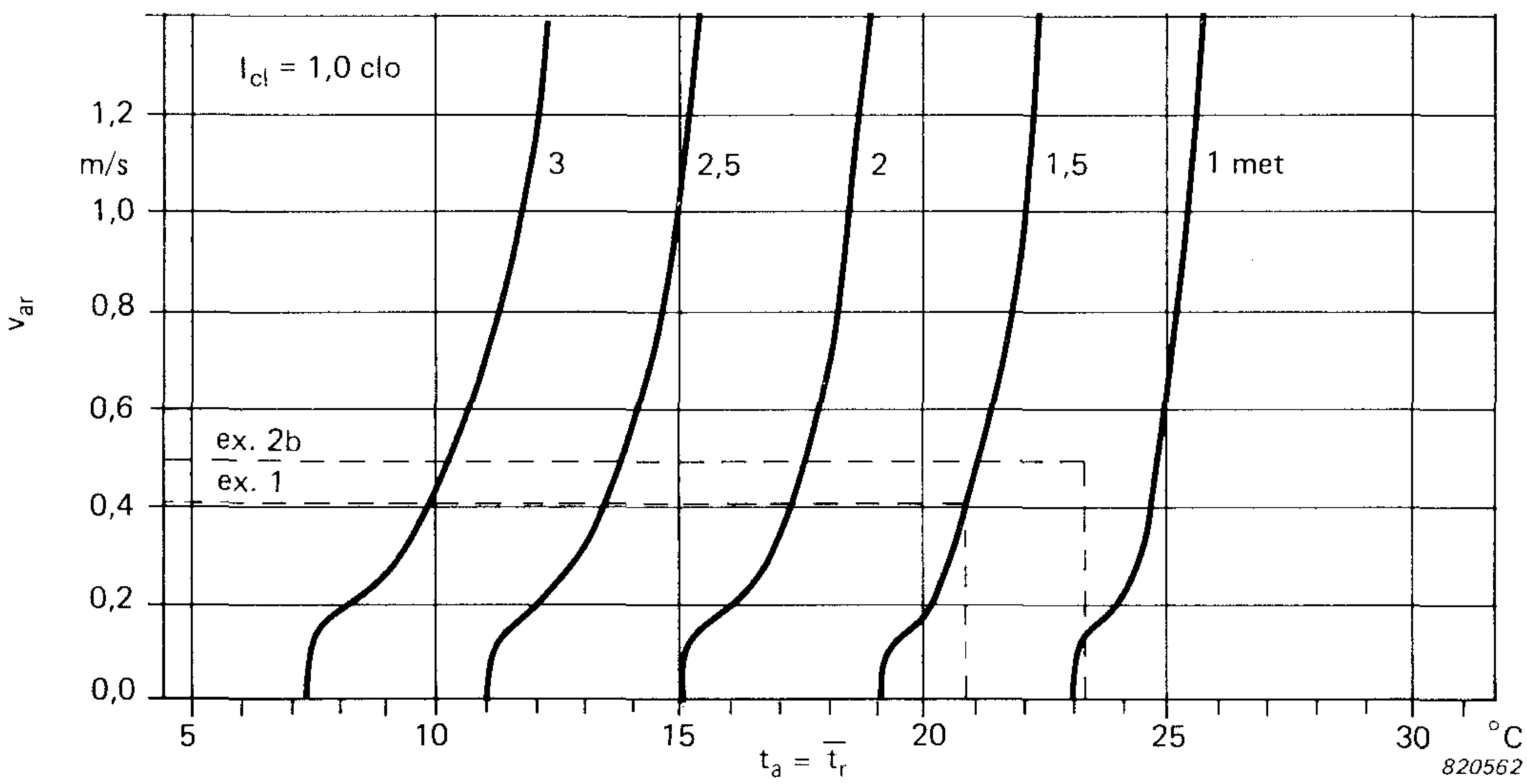


Fig. 5. Comfort lines for 1,0 clo and Relative Humidity 50%. Relative Velocity v_{ar} as a function of air temperature t_a = mean radiant temperature, $\bar{t}_r$ for various activity M as parameter

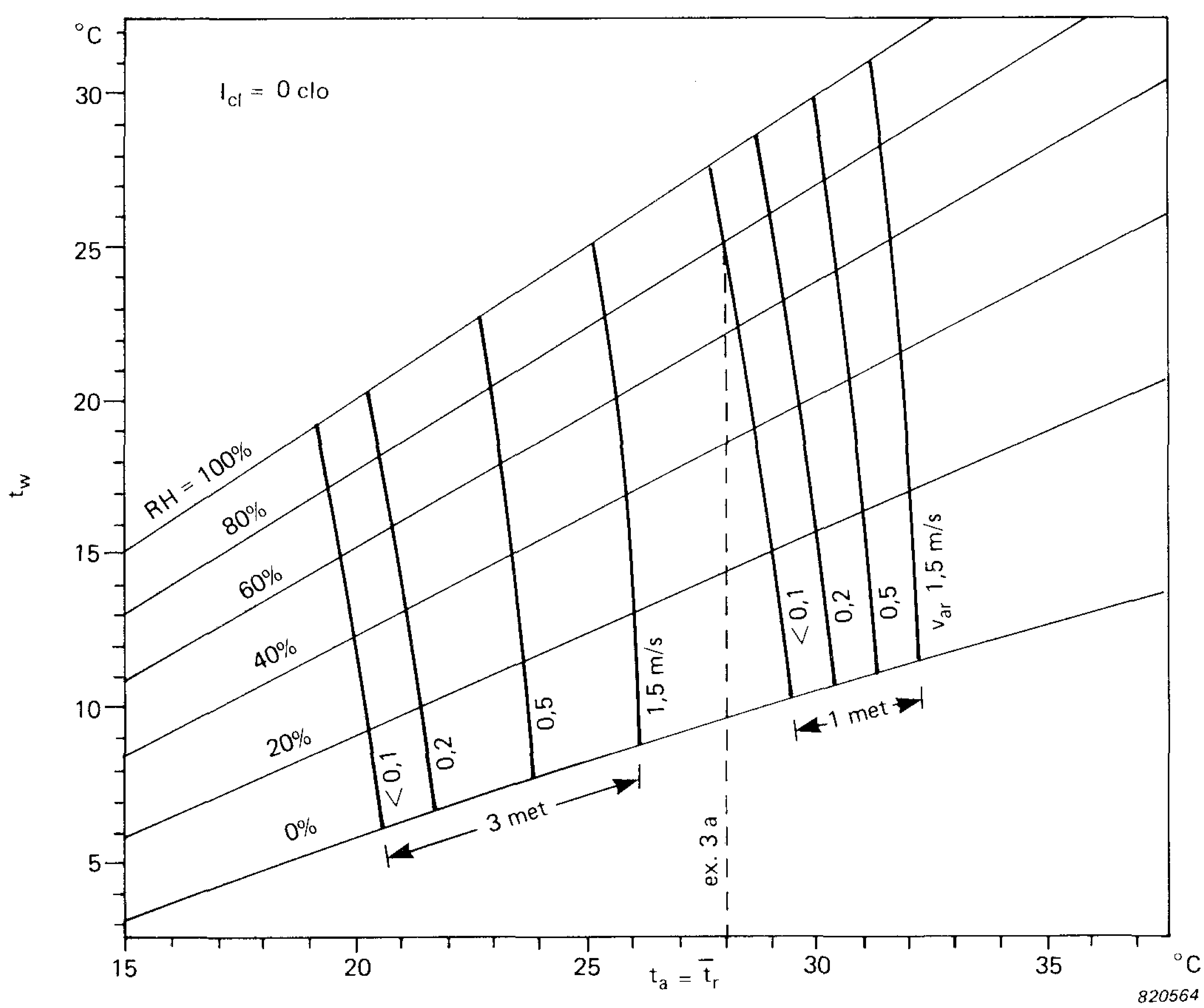


Fig. 6 Comfort lines for 0 clo. Wet bulb temperature t_w as a function of air temperature t_a = mean radiant temperature $\bar{t}_r$ for various relative velocity v_{ar} and activity M as parameters

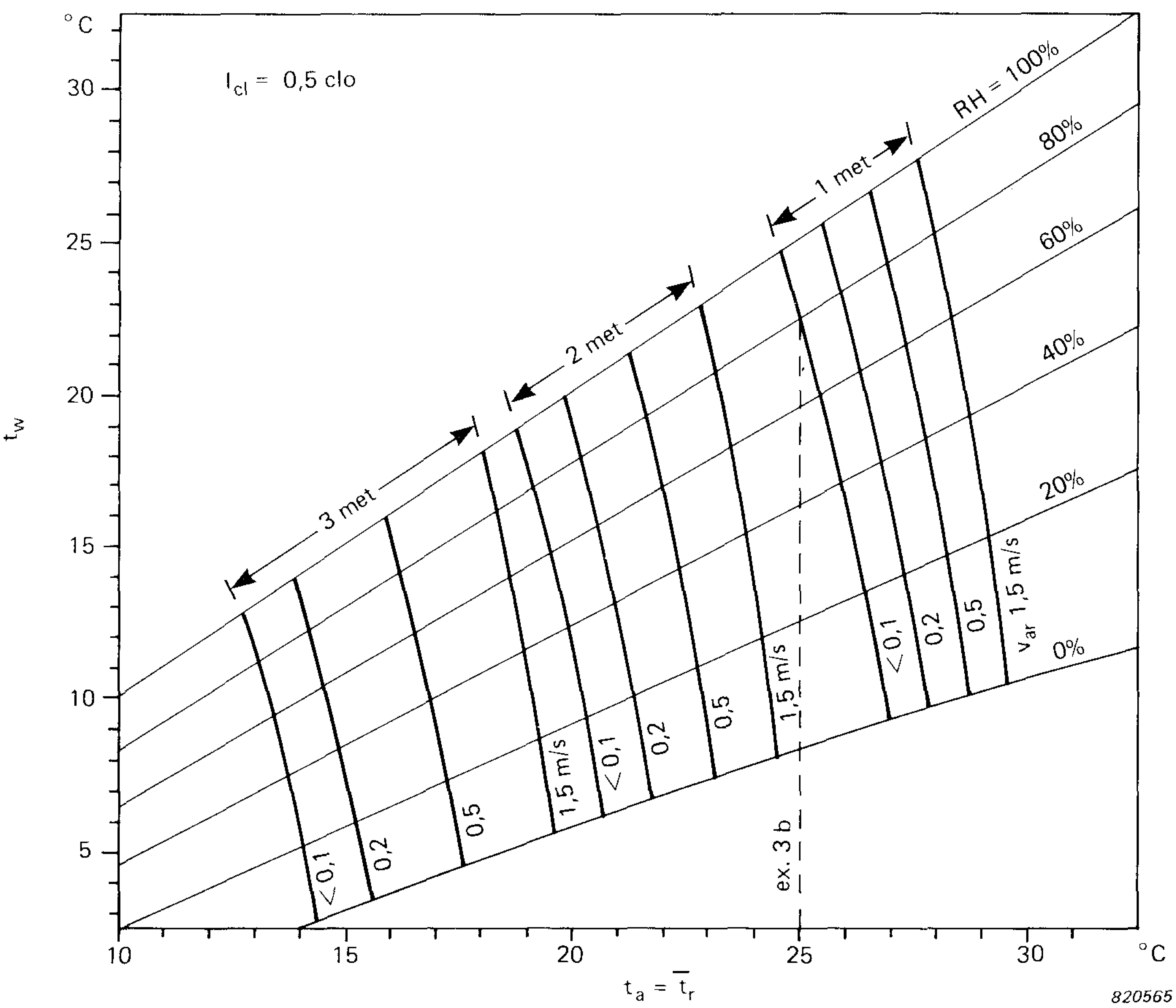


Fig. 7. Comfort lines for 0,5 clo. Wet bulb temperature t_w as a function of air temperature t_a = mean radiant temperature $\bar{t}_r$ for various relative velocity v_{ar} and activity M as parameters

By solving the Comfort Equation it is also possible to estimate separately the heat loss due to radiation, convection and evaporation, as shown in Table 3.

Example 1

It is desired to determine the comfort temperature for the personnel in a shop, where the mean activity corresponds to walking at a speed of 1,5 km/h (activity = 1,5 met ~90 W/m^2), clothing = 1,0 clo, relative humidity = 50%. Owing to the walking, the personnel are exposed to a relative air velocity v_{ar} = 1,5 × 1000/3600 = 0,4 m/s. From Fig.5 it will be seen that the Comfort Temperature $(t_a = \bar{t}_r)$ = 20,8°C.

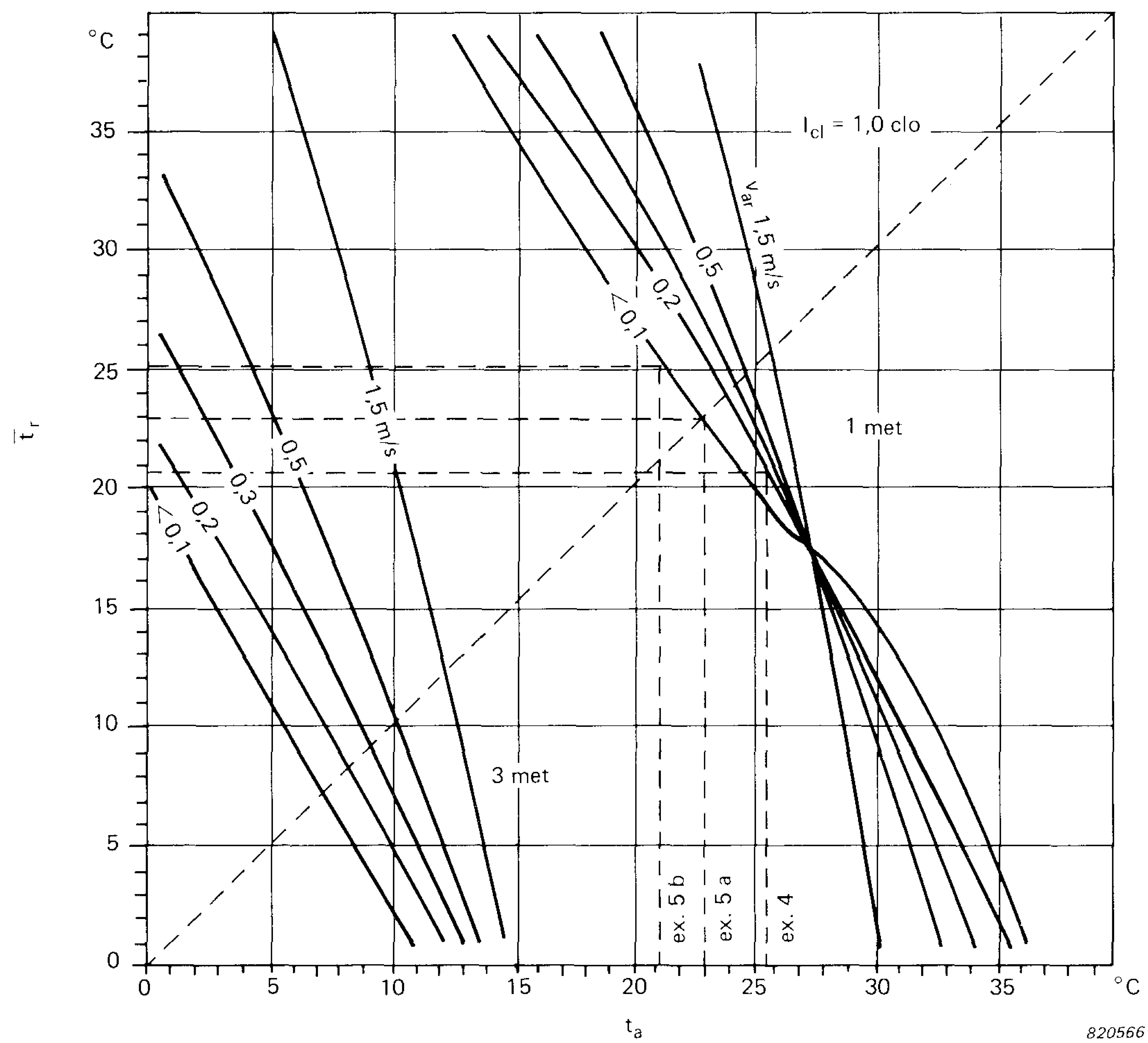


Fig. 8. Comfort lines for 1,0 clo. Mean radiant temperature $\bar{t}_r$ as a function of ambient temperature t_a for various relative velocities v_{ar} and activity M as parameters

Example 2

a) In a "clean room" (laminar flow type) the horizontal air velocity is 0,5 m/s and the personnel are engaged in sedentary work (1,2 met ~ 70 W/m^2), clothed in a light laboratory uniform (0,5 clo). Relative humidity = 50%. By interpolation in Fig.4 it is seen that the Comfort Temperature *(t_a = $\bar{t}_r$)* = 26,6°C.

b) To save energy in winter it is desired to provide the personnel with a special standard suit (1,0 clo). By interpolation in Fig.5 it is seen that the Comfort Temperature *(t_a = $\bar{t}_r$)* can be lowered to 23,3°C.

ENVIRONMENTAL PARAMETERS							ESTIMATED VALUES							
								HEAT LOSSES W						
Activity	Clothing clo	Air Vel. m/s	Humidity kPa	Humidity % RH	Air Temp. °C	Mean Radiant Temp. °C	Clothing Temp. °C	Respiration	Diffusion	Evap. Sweat	Radiation	Convection	TOTAL Evap. Resp.	TOTAL Dry
Seated	0,1	0,1	1,8	50	27,2	27,2	33,0	11	19	9	46	41	38	88
1,2 met≈	0,5	0,1	1,5	50	24,8	24,8	30,1	11	21	9	45	40	41	85
70 W/m^2	0,5	0,5	1,7	50	26,6	26,6	30,0	11	20	9	29	57	40	86
(126 W)	1,0	0,5	1,4	50	23,3	23,3	26,5	12	21	9	28	56	42	84
	1,0	0,1	1,3	50	21,6	21,6	26,6	13	21	9	43	40	43	83
	1,0	0,1	0,8	30	22,1	22,1	26,9	13	25	9	41	38	47	79
Standing	0,5	0,2	1,4	50	23,0	23,0	28,5	16	20	27	46	59	63	105
1,6 met≈	1,0	0,2	1,1	50	19,1	19,1	24,3	18	21	27	44	58	66	102
93 W/m^2	1,0	0,2	0,6	50	10,0	32,7	24,9	21	25	27	−70	165	73	95
(168 W)														

820296

Table 3. Estimated heat losses due to respiration, diffusion, evaporation, radiation and convection. The heat losses are based on the comfort equation and estimated for different combinations of activity clothing, air temperature, mean radiant temperature, air velocity and humidity. All the listed combinations will provide thermal comfort i.e. PMV = 0

Example 3

a) At swimming baths with rest places it is desired to establish the necessary air temperature which will maintain thermal comfort for sedentary (1 met ~ 60 W/m^2) nude (0 clo) persons. Relative air humidity = 80%, relative air velocity < 0,1 m/s, and air temperature = mean radiant temperature. From Fig.6 the comfort temperature is estimated to be 28,0°C.

b) As swimming baths often are used for competitions it is desired to find the comfort temperature for the spectators dressed in light clothing (0,5 clo) and the same conditions as above. From Fig.7 $t_a = \bar{t}_r = 25{,}1\,°C$.

Example 4

Under winter conditions, the mean radiant temperature in a long-distance bus is calculated to be 5 K lower than the air temperature. It is desired to determine the air temperature necessary for comfort, the passengers being presumed to be seated (1 met ~ 60 W/m^2) without overclothes (1,0 clo) and the velocity being 0,2 m/s (relative humidity RH = 50%). From Fig.8 t_a = 25,5°C and $\bar{t}_r$ = 20,5°C.

Example 5

a) The air-conditioning in a theatre is designed for sedentary people (1 met ~ 60 W/m^2) dressed in 1,0 clo (relative humidity ~ 50%, relative air velocity $<$ 0,1 m/s). It is assumed that the air temperature = mean radiant temperature. In Fig.8 the comfort temperature is found to be 23°C.

b) During a performance, measurements show that the mean radiant temperature is 4 K higher (27°C) than the air temperature. This is due to the radiation from one spectator to the other. The theatre management decide to lower the air temperature to keep the audience in a state of thermal comfort. From Fig.8 it is seen that the air temperature should be 21°C.

Individual Differences

Since human beings are not alike, how is it possible, from an equation, to specify one particular temperature which will provide comfort? The answer is that the Comfort Equation does not necessarily satisfy everyone. It gives, however, combinations of the variables which will provide comfort for the greatest number of people. This is exactly what should be aimed at when a large group of people are gathered together in the same indoor environment (optimal comfort for the group).

It has been found from experiments involving 1300 subjects that the best result attainable is dissatisfaction among 5% of the group [2]. Any deviation from the thermal conditions specified by the Comfort Equation will result in an increase in the percentage of dissatisfied.

In a study with 64 subjects it was found that the standard deviation on the preferred ambient temperature was 1,2°C [5].

Comfort Zones or Comfort Points

In times past it was common practice to recommend so-called "comfort zones". How is it then possible that for set values of the parameters the Comfort Equation establishes only one comfort temperature and not a comfort zone? It is true that for each person there exists an interval of ambient temperatures within which he will feel reasonably comfortable.

Thus for each individual there exists a comfort zone. But as the comfort zone varies from person to person there will be no common interval of temperatures for a large group of persons which will satisfy them all. There will not even be one common temperature which will provide comfort for all. But, as mentioned earlier, there will be one ambient temperature at which the least possible number of persons will be dissatisfied (5%). This "comfort point" is established by the Comfort Equation.

Variability in Man's Comfort Conditions from day to day
How reproducible are the comfort conditions for the individual? Is not the subjective thermal sensation so uncertain that large variations in comfort requirements can be expected from day to day? This has been investigated by determining the preferred ambient temperature for each subject under identical conditions on four different days [4]. A standard deviation of only 0,6°C was found.

It is concluded that the comfort conditions for the individual can be reproduced and will vary only slightly from day to day.

Age
It has often been claimed that because metabolism decreases slightly with age the comfort conditions based on experiments with young and

Study	Mean age (yr)	Preferred ambient temp. (°C)	Mean skin temp. at comfort (°C)	Evaporative weight loss during comfort ($g/m^2/hr$)	Number of sub-jects
Nevins et al. [23]	21	25.6			720
Fanger [2]	23	25.6		19.2	128
Fanger [2]	68	25.7		15.3	128
Rohles and Johnson [30]	74	24.5			228
Fanger & Langkilde [5]	23	25.0	33.5	18.0	64
Langekilde [15]	84	25.4	33.2	12.4	16
Comfort equation, Fanger [2]		25.6			

Subjects were tested under the following standardized conditions: sedentary activity, light standard clothing 0-6 clo, rel. velocity <0,1 m/s, rel. humidity 50%, mean radiant temperature = air temperature.

Table 4. Comparison between comfort conditions for different age groups

healthy subjects cannot be used as a matter of course for other age groups. In Table 4 the results are summarized of comfort studies in Denmark and the United States of America on different age groups (mean age 21 to 84 years), [2, 5, 15, 23, 30]. Activity, clothing, and other experimental conditions have in all studies been identical. Subjects during one experiment are seen in Fig. 9. It will be seen from Table 4 that the thermal environments preferred by the elderly do not appear to differ from those preferred by younger people. The lower metabolism in elderly people seems to be compensated for by a lower evaporative loss. This has recently been confirmed in a study by Collins and Hoinville [1].

The fact that young and elderly prefer the same thermal environment does not necessarily mean that they are equally sensitive when exposed to cold (or heat). In practice the ambient temperature level in homes of elderly are often found to be higher than for younger people. This is easily explained by the lower activity level of elderly people, who normally are seated a greater part of the day.

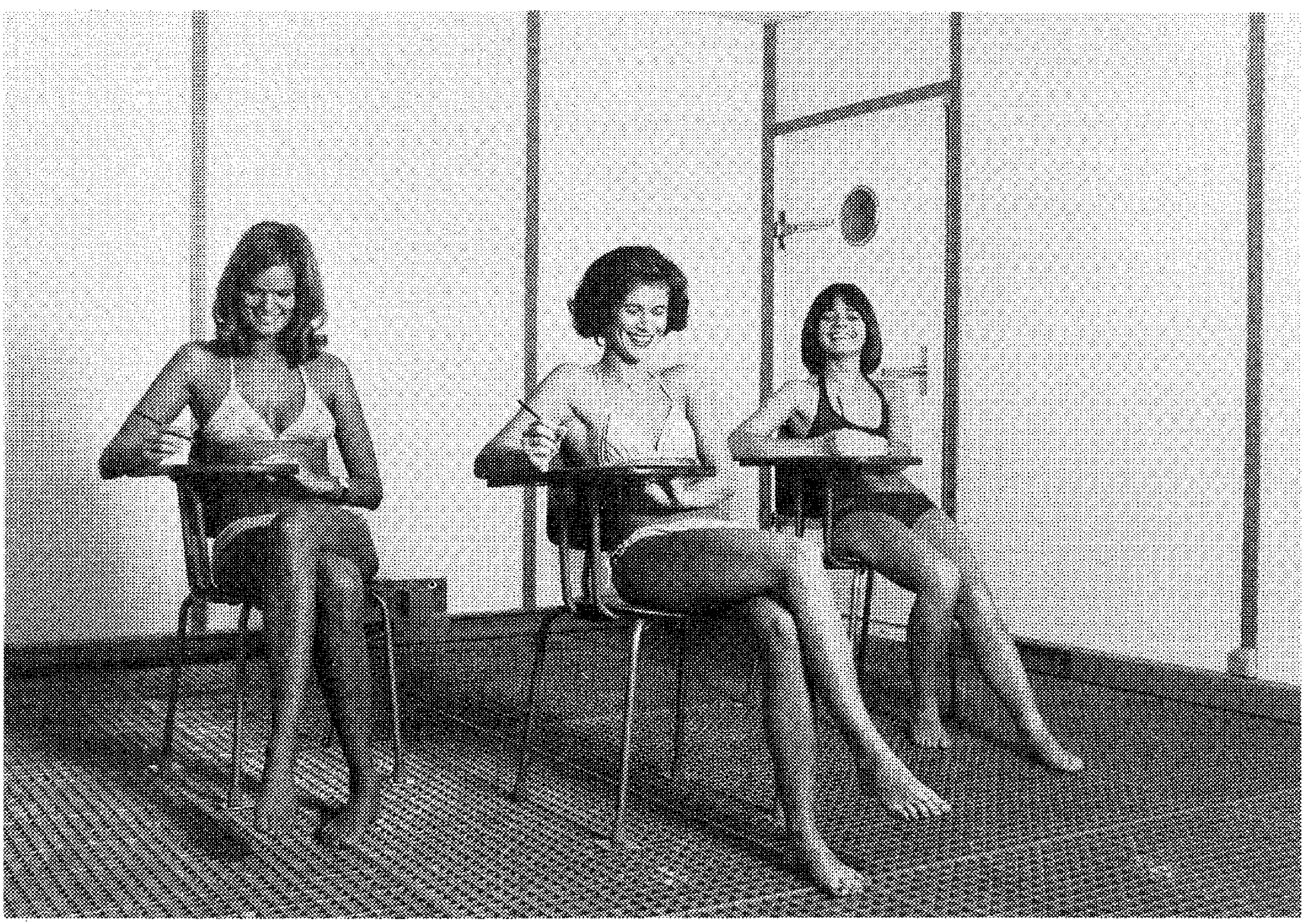


Fig. 9. Experiments with subjects in a climatic chamber

Adaptation

It is widely believed that, by exposure to hot or cold surroundings, people can acclimatise themselves so that they prefer other thermal environments, and that the comfort conditions vary in different parts of the world, depending on the outdoor climate at the relevant place. In Table 5 the results are shown of experiments (identical experimental conditions) involving subjects from the United States of America, Denmark, and tropical countries. The latter group was tested in Copenhagen immediately after their arrival by plane from the tropics where they had lived all their lives.

Moreover, Table 5 gives experimental results for two groups of persons exposed daily to cold. One group comprises persons who for eight hours daily for at least one year have been doing sedentary work in cold surroundings in the meat packing industry. The other group consists of winter swimmers who bathe daily in the sea.

Group	Study	Preferred ambient temp. (°C)	Mean skin temp. at comfort (°C)	Evaporative weight loss during Comfort ($g/m^2/hr$)	Number of subjects
Americans	Nevins et al. [23]	25.6			720
Danes	Fanger [2]	25.7			256
Danes	Fanger and Langkilde [5]	25.0	33.5	18.0	64
People from the tropics	Technical University of Denmark (1972)[1]	26.2	33.5	17.1	16
Danes working in the cold meat-packing industry	Fanger [8]	24.7	33.6	17.1	16
Danish winter swimmers	Fanger et al. [9]	25.0	33.3	16.6	16
Comfort equation	Fanger [2]	25.6			

[1] Data not yet published

Subjects were tested under the following standardized conditions: Sedentary activity, light standard clothing 0-6 clo, rel. velocity < 0,1 m/s, rel. humidity 50%, mean radiant temperature = air temperature.

Table 5. Comparison between comfort conditions for different national-geographic groups and for groups of people regularly exposed to extreme cold or heat

It is apparent from the Table that there are only slight differences between the various groups as regards both the preferred ambient temperature and the physiological parameters in the comfort condition. The results indicate that man cannot become adapted to prefer warmer or colder environments.

It is therefore likely that the same comfort conditions can be applied throughout the world. However, in determining the preferred ambient temperature from the comfort diagrams, a clo-value should be used which corresponds to the local clothing habits. A comparison of field comfort studies from differents parts of the world [24] shows, as might be expected, significant differences in clothing habits depending, among other things, on the outdoor climate.

According to the above results adaptation has no influence on the preferred ambient temperatures. In uncomfortable warm or cold environments there will however often be an influence of adaptation. People used to working and living in warm climates can more easily accept and maintain a higher work performance in hot environments than people from colder climates.

Sex

In all the experiments mentioned in Tables 4 and 5, an equal number of male and female subjects participated, and it is therefore possible to compare the comfort conditions for the two sexes (Table 6). It is shown

Study	Sex	Preferred ambient temp. (°C)	Mean skin temp. at comfort (°C)	Evaporative weight loss during comfort ($g/m^2/hr$)	Number of sub-jects
Nevins et al. [23] and Fanger [2] (both studies combined)	Males Females	25.4 25.8			488 488
Fanger & Langkilde [5]	Males Females	25.0 25.1	33.6 33.4	19.5 16.6	32 32
Comfort equation Fanger [2]		25.6			

Subjects were tested under the following standardized conditions: Sedentary activity: light standard clothing 0.6 clo, rel. velocity $< 0{,}1$ m/s, rel. humidity 50%, mean radiant temperature = air temperature.

Table 6. Comparison between comfort conditions for males and females

that men and women seem to prefer almost the same thermal environments. Women's skin temperature and evaporative loss are slightly lower than those for men, and this balances the somewhat lower metabolism of women.

The reason why women often prefer higher ambient temperatures than men may be explained by the lighter clothing normally worn by women.

Seasonable and Circadian Rhythm

As it has been ascertained above that man cannot becomed adapted to prefer warmer or colder environments, it follows that there is no difference between comfort conditions in winter and in summer. This is confirmed by an investigation undertaken at Kansas State University where results of winter and summer experiments showed no difference [21].

On the other hand, it is reasonable to expect the comfort conditions to alter during the day as the internal body temperature has a daily rhythm, a maximum occurring late in the afternoon and a minimum early in the morning.

This has been studied by determining experimentally the preferred ambient temperature for each of 16 subjects both in the morning and in

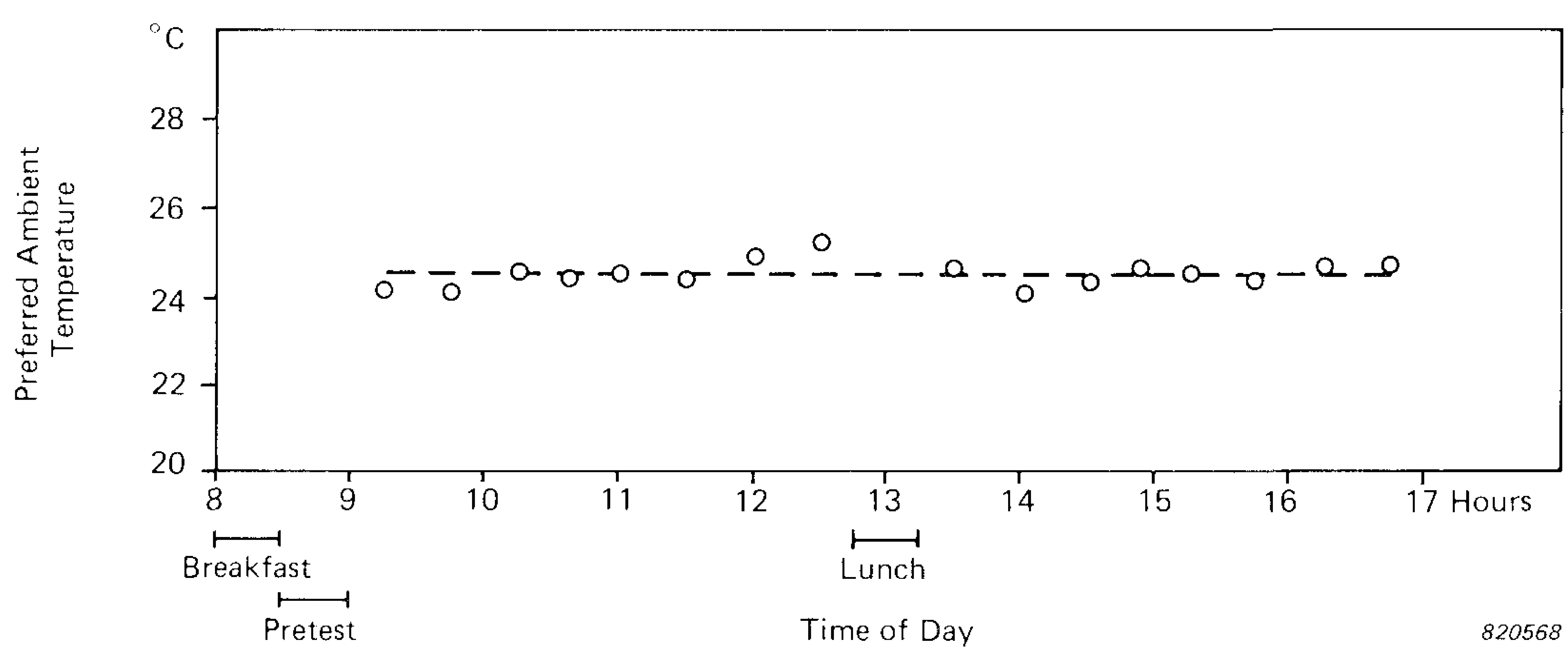


Fig. 10. Mean of the preferred ambient temperature for 16 subjects during a simulated normal 8-hour working day. Sedentary activity. Clothing: 0,6 clo, Relative Air Velocity < 0,1 m/s, Relative Humidity: 50 percent. Mean Radiant Temperature = Air Temperature

the evening. No difference was observed [6, 32]. Furthermore, the preferred ambient temperature during a simulated eight-hour working day (sedentary work) has been studied [3]. It can be seen from Fig.10 that only small fluctuations in the preferred ambient temperature during the day was observed. There is a slight tendency to prefer somewhat warmer surroundings before lunch, but none of the fluctuations is significant.

Colour and Noise

During the energy crisis the idea was put forward that by using "warm" colours (red and yellow) on walls or by the use of reddish lighting, a psychological feeling of heat could be conveyed to people, so that thermal comfort could possibly be maintained at lower ambient temperatures. Similarly, in summer, "cold" colours should be aimed at, or blue lighting used. Some people have even spoken of "colour conditioning" rooms instead of air-conditioning them.

Unfortunately, no energy saving seems to be involved in such measures. Fanger *et al.* [10] studied subjects in rooms with blue or red lighting but found no practical difference in the temperature preferred. Neither did the noise level have any psychological effect on man's thermal comfort.

PMV – PPD index

For technical or economical reasons a thermal environment which will provide optimal thermal comfort is not always possible. It is then often of value to quantify the degree of discomfort, and for this purpose an index has been devised [2] which gives the predicted mean vote (PMV) of a large group of subjects according to the following psycho-physical scale:

+3	hot
+2	warm
+1	slightly warm
0	neutral
–1	slightly cool
–2	cool
–3	cold

The PMV value is determined from tables given in Ref. [2] or from the following equation.

$$PMV = (0{,}303\, e^{-0{,}036M} + 0{,}028) \Big[(M-W)$$

$$- 3{,}05 \cdot 10^{-3} \Big\{ 5733 - 6{,}99\,(M-W) - p_a \Big\} - 0{,}42 \Big\{ (M-W) - 58{,}15 \Big\}$$

$$- 1{,}7 \cdot 10^{-5}\, M\,(5867 - p_a) - 0{,}0014\, M\,(34 - t_a)$$

$$- 3{,}96 \cdot 10^{-8} f_{cl} \Big\{ (t_{cl} + 273)^4 - (\bar{t}_r + 273)^4 \Big\} - f_{cl} h_c (t_{cl} - t_a) \Big] \quad (21)$$

where

$$t_{cl} = 35{,}7 - 0{,}028\,(M-W) - 0{,}155\, I_{cl} \Big[3{,}96 \cdot 10^{-8} f_{cl} \Big\{ (t_{cl} + 273)^4$$

$$- (\bar{t}_r + 273)^4 \Big\} + f_{cl} h_{cl} (t_{cl} - t_a) \Big]$$

$$h_c = \begin{cases} 2{,}38\,(t_{cl} - t_a)^{0{,}25} & \text{for } 2{,}38\,(t_{cl} - t_a)^{0{,}25} > 12{,}1\sqrt{v_{ar}} \\ 12{,}1\sqrt{v_{ar}} & \text{for } 2{,}38\,(t_{cl} - t_a)^{0{,}25} < 12{,}1\sqrt{v_{ar}} \end{cases}$$

$$f_{cl} = \begin{cases} 1{,}00 + 0{,}2\, I_{cl} \text{ for } I_{cl} < 0{,}5 \text{ clo} \\ 1{,}05 + 0{,}1\, I_{cl} \text{ for } I_{cl} > 0{,}5 \text{ clo} \end{cases}$$

PMV = Predicted Mean Vote
M = Metabolism, W/m^2 (1 met = 58,15 W/m^2)
W = External work, met. Equal to zero for most metabolisms
I_{cl} = Thermal resistance of clothing, clo (1 clo = 0,155 m^2 K/W)
f_{cl} = The ratio of the surface area of the clothed body to the surface area of the nude body
t_a = Air temperature, °C
$\bar{t}_r$ = the mean radiant temperature, °C
v_{ar} = Relative air velocity, m/s
p_a = Water vapour pressure, Pa
h_c = Convective heat transfer coefficient, W/m^{2}K
t_{cl} = Surface temperature of clothing, °C

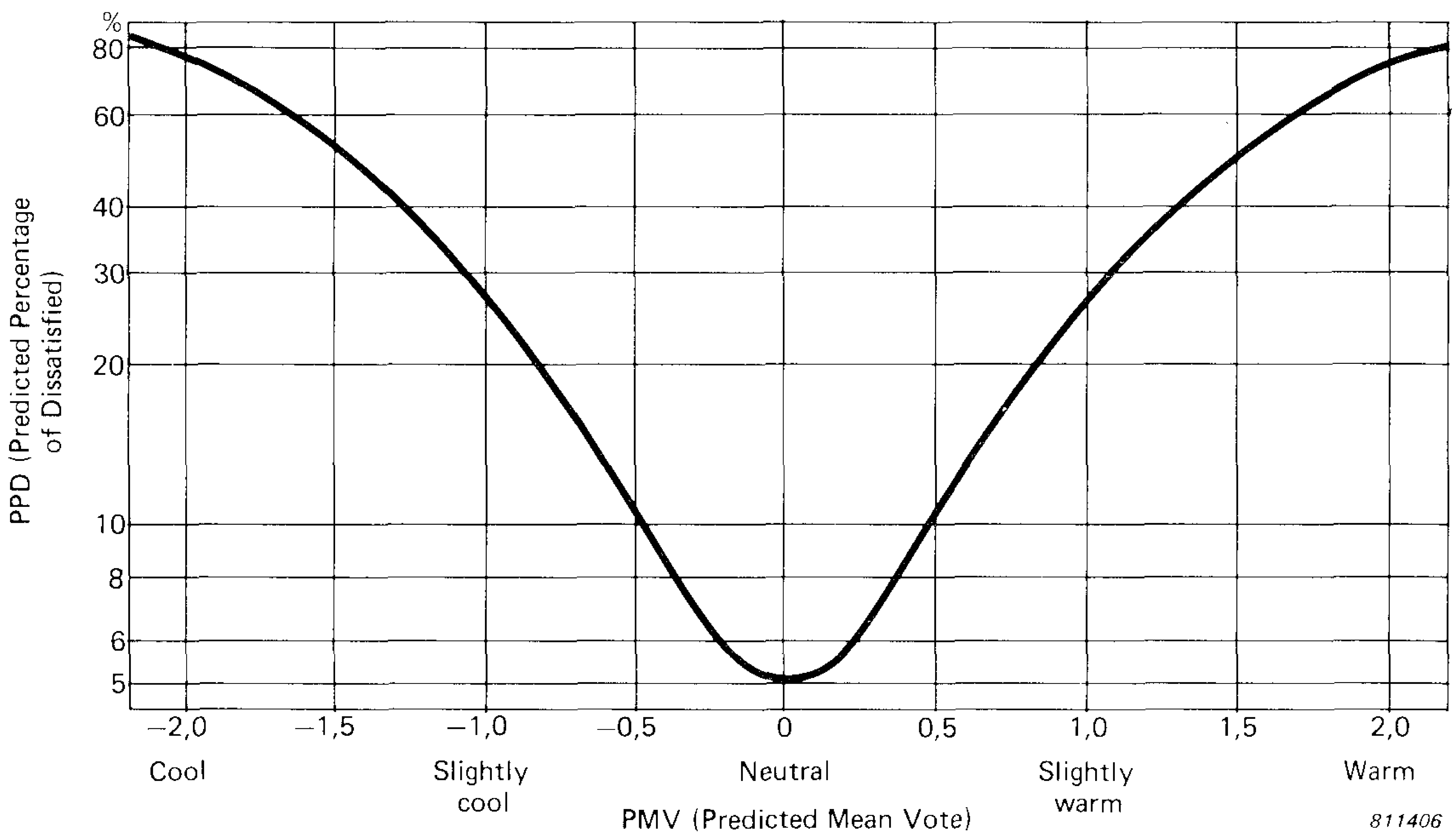


Fig. 11. The relationship between PPD (Predicted Percentage of dissatisfied) and PMV (Predicted Mean Vote)

The predicted percentage of dissatisfied (PPD), may then be estimated from Fig.11. When PMV is set to zero the comfort equation is established.

Fig.11 is based on studies comprising a group of 1300 subjects. As mentioned earlier, 5% is the lowest percentage of dissatisfied which can be expected. The PPD value is an appropriate and easily understood expression for the quality of a given thermal environment.

Fig.12 shows the predicted percentage of dissatisfied as a function of the operative temperature for a typical summer and winter situation.

The PMV–PPD index has now been suggested by ISO (DIS 7730) in a standard for evaluating moderate thermal environments. It has been recommended to use the limits

$$\begin{aligned} -0{,}5 < PMV &< 0{,}5 \\ PPD &< 10\% \end{aligned} \tag{22}$$

for an acceptable thermal environment. The same range has also been adopted by the ASHRAE standard for thermal environments and in a

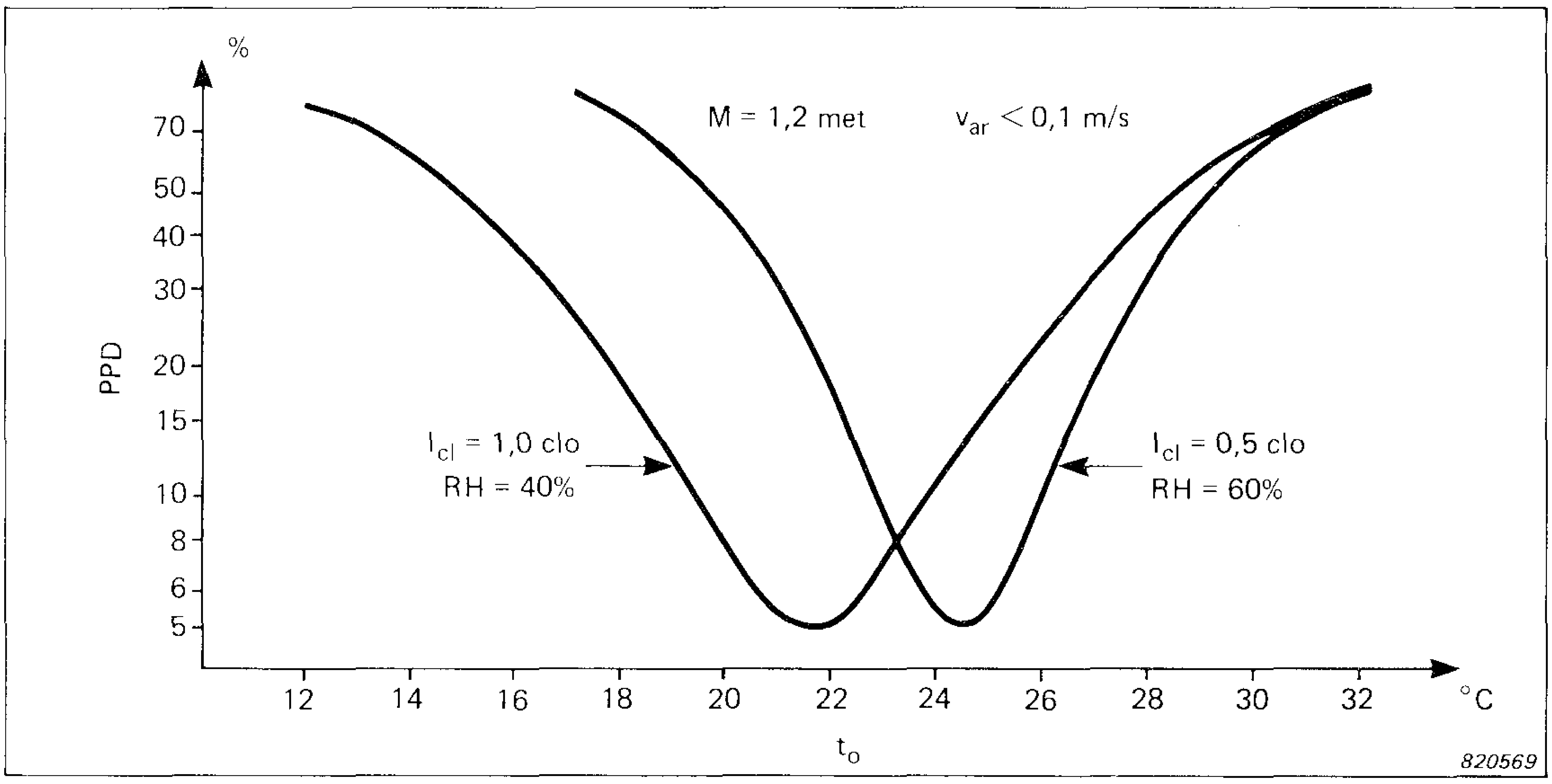


Fig. 12. The relation between operative temperature, t_0, and Predicted Percentage of Dissatisfied (PPD) for winter (clothing I_{cl} = 1,0 clo) and summer (clothing I_{cl} = 0,5 clo) conditions. Activity, M = 1,2 met, Relative Air Velocity, v_{ar} <0,1 m/s and Relative Humidity RH = 40% in winter and RH = 60% in summer

new proposal from NKB (Nordic Committee on Building regulations). In both standards the limits are however not specified directly in PMV-values but as a corresponding operative temperature interval depending on the given combination of clothing and activity.

Local Thermal Discomfort

Thermal neutrality as predicted by the Comfort Equation, i.e. PMV = 0, is not the only condition for thermal comfort. A person may feel thermally neutral for the body as a whole, but he might not be comfortable if one part of the body is warm and another cold. It is therefore a further requirement for thermal comfort that no local warm or cold discomfort exists at any part of the human body. Such local discomfort may be caused by an asymmetric radiant field (cold windows, warm heaters), by a local convective cooling (draught), by contact with a warm or cool floor (floor heating) or by a vertical air temperature difference between feet and head. Until now rather few studies on these problems have been reported [11, 14, 17, 18, 19, 20, 22, 26, 27, 28, 29] and more research is needed. Especially the combined effect of general thermal comfort and local thermal discomfort need to be studied.

People who are generally cool i.e. PMV < 0 are more sensitive to draught and people who are generally warm PMV>0 will be more sensitive to a heated ceiling. If people are in general thermal comfort PMV~0 then the risk for local thermal discomfort will be less.

Thermal Comfort Meter, Type 1212

When evaluating an existing thermal environment it is necessary to verify that the temperature level is acceptable for the actual combination of activity and clothing (thermal neutrality). The PMV-PPD index has to be estimated. One method is to measure the four environmental parameters (air temperature, mean radiant temperature, air velocity, humidity) individually and estimate the actual activity and clothing (clo-value) by means of tables. Then the PMV value may be calculated according to the equation or found in tables. Another method is to use an integrating measuring principle as implemented in the Thermal Comfort Meter, Type 1212. (Fig.13)

The size and shape of the heated transducer is chosen such that the relation between the heat losses by convection and radiation is the same as for a human being, and such that the angle factors in the different directions are comparable with the angle factors for a person.

The actual clothing (clo), activity (met) and vapour pressure (kPa) are set on the instrument. The Transducer MM 0023 is heated to a surface temperature which is equal to the clothing surface temperature of a person in a state of thermal comfort dressed in the clothing set on the

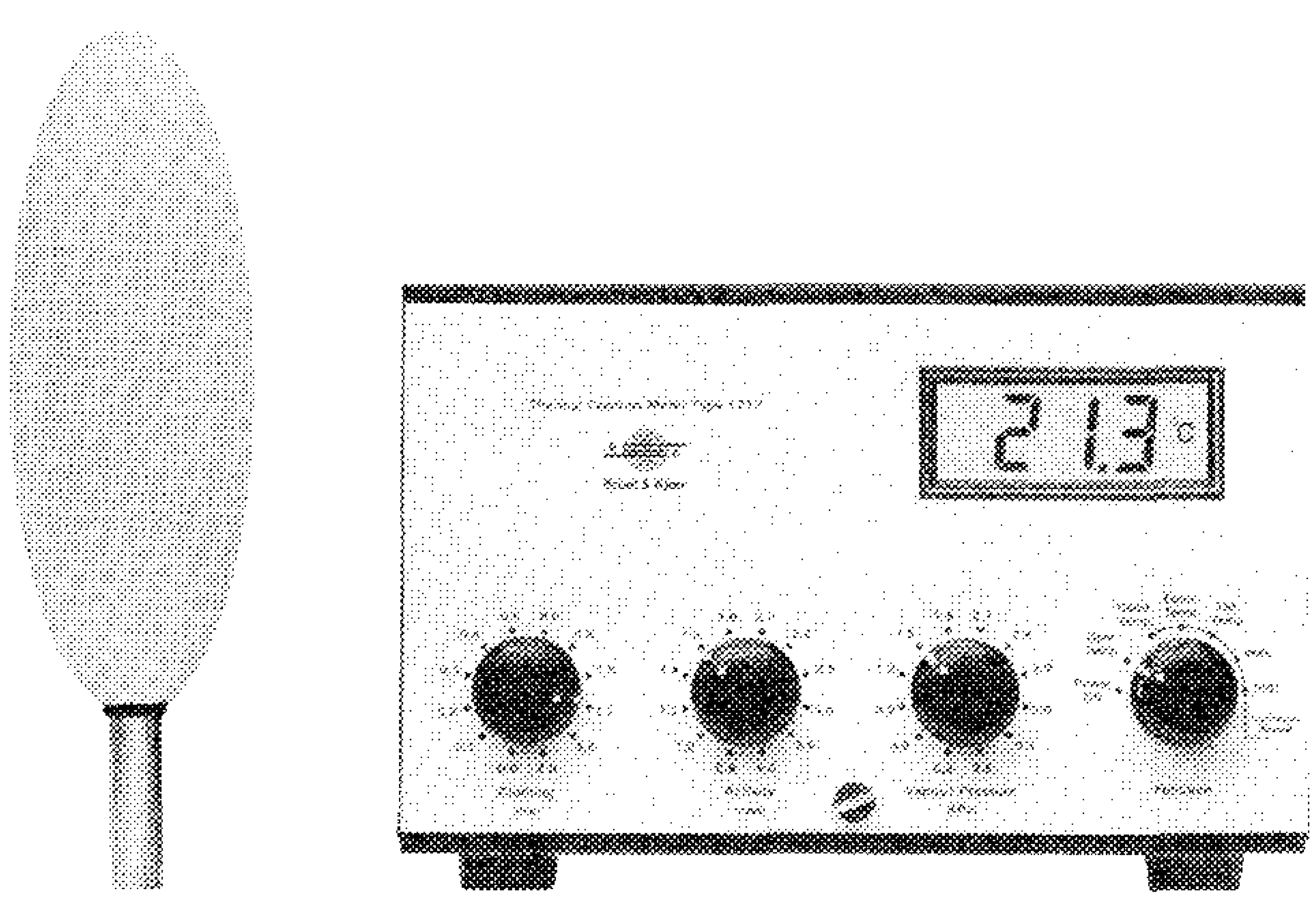


Fig. 13. Thermal Comfort Meter Type 1212

instrument. The applied heating power (W/m^2) is then a measure of the dry heat loss from the person to the environment. The corresponding Equivalent Temperature (see below) is then calculated and compared with the Comfort Temperature estimated from the set combination of clothing, activity and vapour pressure. The instrument also calculates the corresponding PMV and PPD value.

The instrument has various functions besides the direct measurement of the PMV and PPD value. The **Operative Temperature** is measured with the Transducer unheated, as the form and size of the Transducer result in a correctly weighted value of the air and mean radiant temperature. In the **"Comf. Temp."** position the instrument is used as a calculator estimating the Comfort Temperature for the set combination of clothing, activity and vapour pressure. In the **"Equiv. Temp."** position the temperature level is measured integrating the air and mean radiant temperature and the air velocity to one value, the "Equivalent Temperature"; i.e., the cooling effect of an increased air velocity is transformed to a decrease in temperature that will provide the same cooling on a person at an air velocity equal to 0 m/s. In the **"Dif. Temp."** position it is possible to read directly the temperature change necessary to reach optimal conditions, i.e. the Comfort Temperature.

References

[1] COLLINS, K.J. & HOINVILLE, E. — "Temperature requirements in old age." *Building Services Engineering Research and Technology,* Vol.1, No.4, 1980, pp.165–172.

[2] FANGER, P.O. — *Thermal Comfort.* McGraw-Hill Book Company, New York, 1973, 244 p.

[3] FANGER, P.O., HØJBJERRE, J. & THOMSEN, J.O.B. — "Man's preferred ambient temperature during the day." *Arch. Sci. Physiol.*, 27(4): A395–A402, 1973.

[4] FANGER, P.O. — "The variability of man's preferred ambient temperature from day to day." *Arch. Sci. Physiol.*, 27(4): A403–A407, 1973.

[5] FANGER, P.O. & LANGKILDE, G. "Interindividual differences in ambient temperatures preferred by seated persons." *ASHRAE Trans.*, 81, 21140–147, 1975.

[6] FANGER, P.O., HØJBJERRE & THOMSEN, J.O.B. "Thermal comfort conditions in the morning and in the evening." *Int. J. Biometeor.*, 18, 1:16–22, 1974.

[7] FANGER, P.O., ÖSTBERG, A.G., McK.NICHOLL,A.G., BREUM, N.O. & JERKING, E. "Thermal comfort conditions during day and night." *Europ. J. Physiol.*, 33:255–263, 1974.

[8] FANGER, P.O. "Can exposure to cold cause people to prefer lower room temperatures?" *Proc.* of the *"IIR International Conference on Food Science, Refrigeration and Air Conditioning"*, Melbourne, 1976, pp. 697–704.

[9] FANGER, P.O., HØJBJERRE, J. & THOMSEN, J.O.B. "Can winter swimming cause people to prefer lower room temperatures?" *Int. J. Biometero.*, 21, 1:44–50, 1977.

[10] FANGER, P.O., BREUM, N.O. & JERKING, E. "Can colour and noise influence man's thermal comfort?" *Ergonomics,* 20, 1:11–18, 1977.

[11] FANGER, P.O. & PEDERSEN, C.J.K. "Discomfort Due to Air Velocities in Spaces". *Proc. of the meeting of Commissions B1, B2, E1 of the IIR,* Belgrade 1977/4, pp.289–296.

[12] GOLDMAN, R.F. "Clothing design for comfort and work performance in extreme thermal environments." *Trans. of the New York Academy of Sciences.* Series II, VOl.36, no.6. pp 531–544, 1974.

[13] GOLDMAN, R.F. "Clothing, its physiological effects, adequacy in extreme thermal environments, and possibility of future improvements." *Arch. Sci. Physiol.*, 1973, Vol.27, A 137–A 147.

[14] HOUGHTEN, F.C. "Draft Temperatures and Velocities in Relation to Skin Temperature and Feeling of Warmth". *ASHVE Trans.*, 44:289, 1938.

[15] LANGKILDE, G. "Thermal comfort for people of high age." In J. Durand and J. Raynaud (eds.): *Confort thermique: Aspects physiologiques et psychologiques*. INSERM, Paris 1979, 75:187–193.

[16] "Luftkvalitet och Termisk Inomhusklimat", *Nordic Indoor Climate Standard,* NKB (The Nordic Committee on Building Regulation), Stockholm, 1981

[17] McINTYRE, D.A. "The Thermal Radiation Field". *Building Science,* 9:247–262, 1974.

[18] McINTYRE, D.A., & GRIFFITHS, I.D. "The Effect of Uniform and Asymmetric Thermal Radiation on Comfort". *Proc. of the 6th International Congress of Climatistics* "CLIMA 2000", Milan, March 1975

[19] McINTYRE, D.A. "Overhead Radiation and Comfort". *The Building Services Engineer*, 44:226–232, 1976.

[20] McINTYRE, D.A. "The Effect of Air Movement on Thermal Comfort and Sensation". In P.O. Fanger and O. Valbjørn (eds.): *Indoor Climate,* Danish Building Research Institute, Copenhagen 1979.

[21] McNALL, P., RYAN, P.W. & JAAX, J. "Seasonal variation in comfort conditions for college-age persons in the Middle West." *ASHRAE Transactions,* 74, Part 1, pp. IV.2.1–IV.2.9. (1968).

[22] McNALL, P.E., Jr. & BIDDISON, R.E. "Thermal and Comfort Sensations of Sedentary Persons Exposed to Assymmetric Radiant Fields". *ASHRAE Trans.*, Vol. 76, Part 1, 1970.

[23] NEVINS, R.G., ROHLES, F.H., SPRINGER, W. & FEYERHERM, A.M. "Temperature-humidity chart for thermal comfort of seated persons." *ASHRAE Transactions,* 72, Part I, pp.283–291. (1966).

[24] NICOL, J.F. & HUMPHREYS, M.A. "Thermal comfort as part of a self-regulating system." *Proceedings of CIB symposium on thermal comfort.* Building Research Station, London, September. (1972).

[25] NISHI, Y. & GAGGE, A.P. "Direct evaluation of convective heat transfer coefficient by naphthalene sublimation". *J. of Applied Physiology,* vol.29, No.6, December 1970.

[26] OLESEN, B.W. "Thermal Comfort Requirements for Floors Occupied by People with Bare Feet". *ASHRAE Trans.*, Vol.83, Part 2, 1977.

[27] OLESEN,B.W. "Thermal Comfort Requirements for Floors". *Proc. of the meeting of Commissions B1, B2, E1 of the IIR,* Belgrade 1977/4, pp.337–343.

[28] OLESEN, B.W., SCHØLER, M. & FANGER, P.O. "Vertical Air Temperature Differences and Comfort". In P.O. Fanger and O. Valbjørn (Eds.): *Indoor Climate,* Danish Building Research Institute, Copenhagen 1979, pp. 561–579.

[29] OLESEN, S., FANGER, P.O., JENSEN, P.B. and NIELSEN, O.J. "Comfort Limits for Man Exposed to Asymmetric Thermal Radiation". *Proc. of CIB Symposium on Thermal Comfort,* Building Research Station, London, 1972.

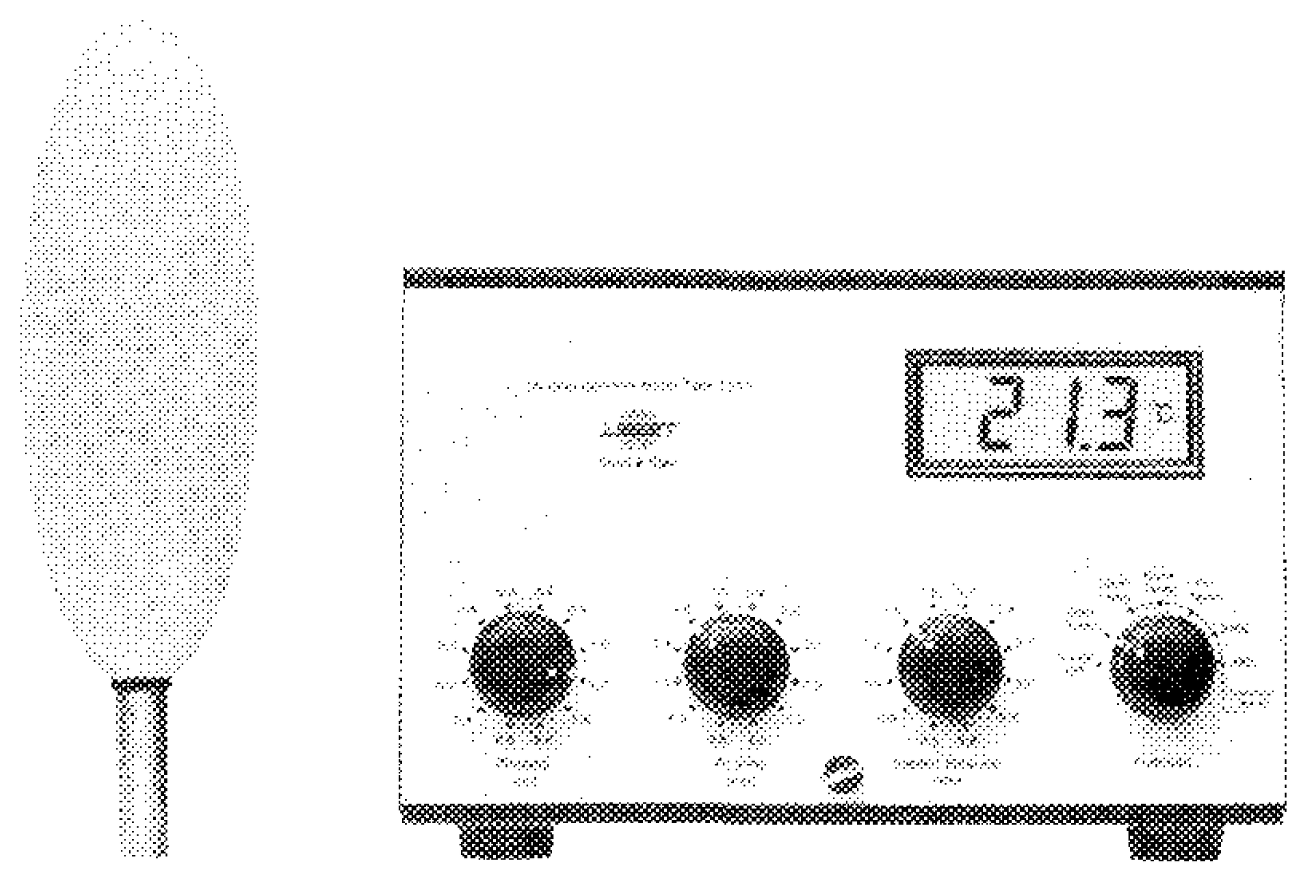
[30] ROHLES, F. & JOHNSON, M.A. "Thermal comfort in the elderly." *ASHRAE Transactions,* 78, Part I, pp. 131–137. (1972)

[31] "Thermal Environmental Conditions for Human Occupancy", *ASHRAE Standard 55–81,* American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, USA, 1981.

[32] ÖSTBERG, O. & McK.NICHOLL, A.G. "The preferred thermal conditions for 'morning' and 'evening' types of subjects during day and night – preliminary results." *Build International,* 6, no.1, pp. 147–157. (1973).

News from the Factory

Thermal Comfort Meter Type 1212



The Thermal Comfort Meter Type 1212 is a direct-reading instrument for determining the effect on human comfort of the thermal characteristics of indoor environments. It conforms to the requirements of ISO Draft Proposal 7730, "Moderate thermal environments — Determination of the thermal indices PMV and PPD and assessment of thermal environments for comfort".

Thermal comfort is a function not only of air temperature, but also of five other, less obvious parameters: mean radiant temperature, air velocity, humidity, activity level, and clothing thermal resistance. When any combination of these factors satisfies the Comfort Equation derived by Prof. P. O. Fanger, the thermal comfort of a majority of individuals can be stated to be neutral. The Type 1212 measures the combined effect of three of these parameters (air velocity, air temperature, and mean radiant temperature), and computes in usable form a quantitative measure of comfort taking account of dialled-in values of the other three parameters.

It consists of a portable, battery-powered instrument which senses environmental conditions via the Comfort Transducer MM 0023. This

Transducer is electronic in its operation and is connected by a cable. It may be mounted on a normal lightweight photographic tripod, and is used in one of two orientations corresponding to standing and seated people. The MM 0023 incorporates a controlled heat source and in this and other respects models the static thermal properties of a human being. It contains a surface temperature sensor, and the output of the heating element is adjusted automatically to warm the surface to a temperature similar to that of a thermally comfortable human being clad as preset on the instrument front-panel Clothing switch. The rate of heat production needed to attain this temperature is used as a measure of the environmental conditions.

Measurements made with the Thermal Comfort Meter may be read directly on its liquid crystal display or logged on a strip-chart recorder such as Types 2306 or 2309 from B & K. Three recorder outputs are provided: *Comfort Temperature* (which is used for calibrating the recorder), *PMV*, and *Displayed Value*. The displayed value can be Operative Temperature, Comfort Temperature, Equivalent Temperature, Difference Temperature, PMV (Predicted Mean Vote), or PPD (Predicted Percentage of Dissatisfied), selected by a switch on the front panel.