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LIMITS FOR DRAUGHT AND ASYMMETRIC RADIATION IN RELATION TO HUMAN THERMAL WELL-BEING

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Over the years many investigations have been made with the aim of determining comfort criteria during occupancy of thermal asymmetric fields.

These investigations fall into two main groups, namely:

1. Asymmetric radiation fields
2. Convection fields

Considering the number of years that elapsed before Fanger's comfort equation /1/ provided a comfort criterion for a homogeneous thermal field, an equation taking all relevant parameters into account, it is not surprising that we still lack a corresponding common expression giving limits for how much the heat loss from various parts of the body may vary without giving rise to feelings of thermal discomfort.

The comfort equation is set up on the basis of comfort votings under optimal thermal conditions - conditions which can be created in a climate chamber but which seldom occur in practice. The asymmetric fields often found can have many causes, some typical examples being:

1. Cold outer walls (windows)
2. Radiation-heated ceilings
3. Cold floors
4. Cold downstream inside large windows
5. Draught from ventilation systems

For all these types of asymmetric thermal influences thermal comfort limits have been set up. But it is obvious that a direct comparison of the different limits is very difficult.

It is therefore desirable to find a single parameter which could indicate whether one of the many asymmetric comfort criteria is exceeded.

In searching for such a characteristic parameter, it is pertinent to examine the physiological reactions which determine a sensation of local thermal discomfort.

The thermoreceptors of the skin.

H.C. Bazett /2/ and H. Hensel /3/ have studied and described the reaction of the skin under different thermal influences. They have determined nerve impulse frequencies from a single thermoreceptor when the skin is exposed to a thermal influence (see Fig. 1). Fig. 2 gives a further example from /3/ of the relation between the surface temperature of the skin and the impulse frequency.

It will be seen how the impulses from the individual receptors accumulate, which explains why the thermal discomfort caused by a constant influence increases with the size of the exposed skin area. But what physical parameter determines this frequency?

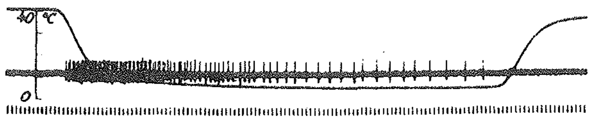

Fig. 1. The variation of the impulse frequency from a single cold receptor fiber as a function of the skin temperature from /3/.

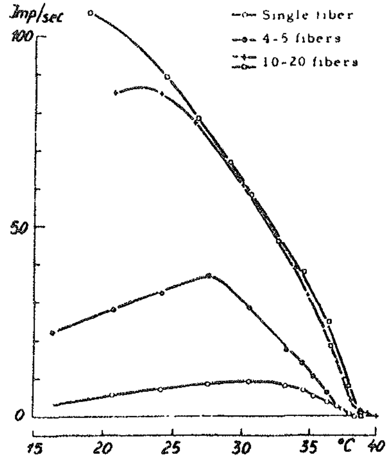

Fig. 2.
Total impulse frequency of the steady discharge in different preparations of the cat lingual nerve as a function of the temperature of the tongue surface. From /3/.

In order to investigate this, an analysis of some typical and known connections between thermal skin influences and the resultant nerve impulse frequencies was made on an electrical analog computer in the laboratory.

Fig. 3 shows the El-model used and indicates thermal conductivity and heat capacity for the skin, the location of the thermoreceptors and other necessary data.

In the El-model, temperature is simulated by voltage, heat flow by current. Thermal capacity corresponds to electrical capacitance and thermal resistance corresponds to electrical resistance.

On this model is now simulated some typical skin temperature variations, the result of which is known in the thermal physiological system.

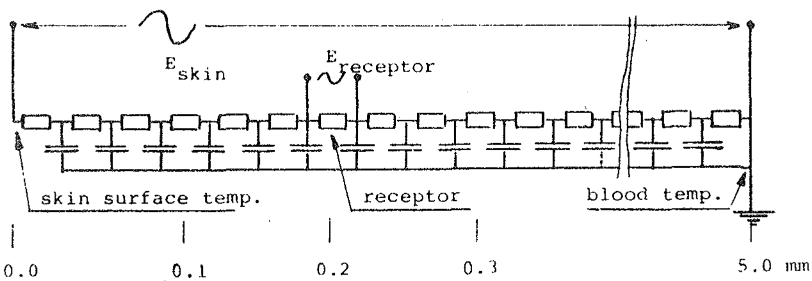

Fig. 3 - Electrical analog model of the outer 5 mm of the human skin. Thermal conductivity: 0,33 W/mC, heat capacity 3,35 J/cm^3 °C, depth of the thermal receptor 0,2 mm.

A. A sudden change in the skin temperature (Fig. 4).

In the El-model is simulated a sudden change in the temperature at the skin surface, and the corresponding change in heat flow through the thermoreceptors is registered.

In Fig. 4 b is shown, for purposes of comparison, the relationship found by Hensel between a sudden temperature change in the skin surface and the impulse frequency from the receptors. It will be seen that there is good agreement in the shape of the curve in Fig. 4a and 4b.

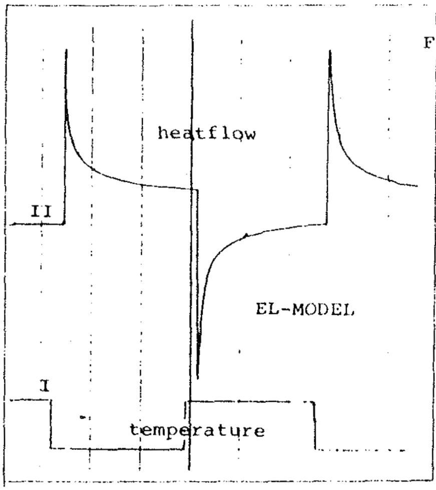

Fig. 4a. A sudden temperature change in the skin surface is in the El-model simulated by suddenly changing the voltage in point A (see Fig. 3). The change is registered by line I. The resultant voltage over the resistance $m_{receptor}$ is registered by line II, which at the same time indicates the cource of the heat flow through the thermoreceptors.

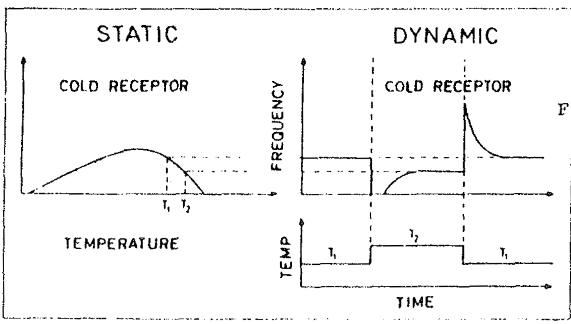

Fig. 4b. Generalized response of cutaneous single cold receptor to constant temperatures (static response) and to rapid temperature changes (dynamic response) from /4/.

B. A slow but constant change in skin surface temperature. (Fig. 5)

Hensel /4/ has performed numerous experiments with the purpose of finding a possible connection between the velocity with which the temperature of the skin changes and the deviation from the comfort temperature which occurs before the sensation of cold or heat is felt.

A result of these experiments is seen in the left part of Fig. 5. Three points are now chosen on the cooling curve and the temperature change corresponding to each of these points is put on the model in the form of triangular voltages with amplitudes corresponding to the temperature difference between the chosen point and 33.3°C, this being the preferred temperature.

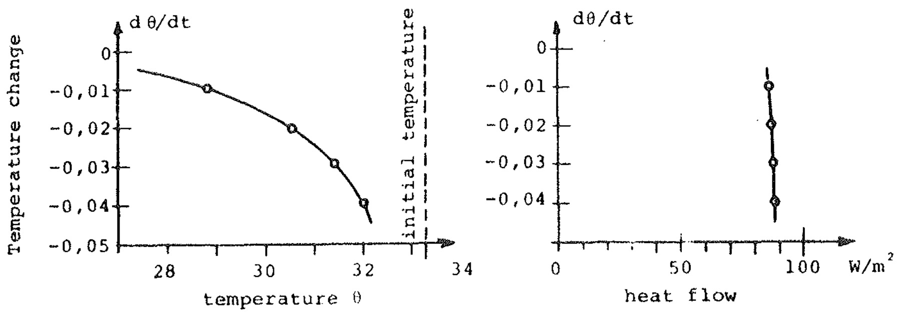

Fig. 5. Left figure: The position of cold threshold in relation to the rate of temperature change $d\theta/dt$, and the temperature θ of the skin where a distinct sensation of cold is felt. Initial temperature in all experiments 33,3°C.
Right figure: Correlation between the skin temperature changes from Hensel's figure and the corresponding heat flow through the receptors at distinct sensation of cold found at the El-analog model. The heat flow is nearly the same for all values of $d\theta/dt$.

It will be seen that the heat flow in all three cases reaches nearly the same level at that temperature at which the feeling of cold in Hensel's experiments is clearly acknowledged.

Both these examples show that it could be the heat flow through the receptors which determines the impulse frequency, which in the brain is converted into a feeling af heat or cold.

The hypothesis might also be used in the temperature-constant case with normal skin temperatures. As seen in Fig. 2, the impulse frequency is almost proportional to the deviation of the skin temperature from the blood temperature. The heat flow will likewise be proportional to this temperature difference.

THE HEAT FLOW THEORY APPLIED TO A NEW COMFORT CRITERIA FOR DRAUGHT

Claus Pedersen /5/ has proved in a recently published paper that the sensation of draught in a given environment depends on the following properties of the local air:

1. Temperature in relation to the temperature of the room air
2. Mean velocity ($\bar{v}$)
3. Velocity variations ($\frac{v_{max}}{\bar{v}}$)
4. Frequency of velocity variations

In his paper no single expression is put forward for determining the influence of an air movement on thermal comfort, but a number of examples of permissible velocities are given, provided that the number of dissatisfied does not exceed 5, 10, 20 or 30%.

In Fig. 6 an example from /5/ is given. It will be seen here how the local smooth air velocities which will give rise to thermal discomfort for 5, 10, 20 and 30%, vary according to the differences between local air temperature and the comfort temperature. On the basis of these curves the heat flow through naked skin exposed to local air movement is calculated. These heat flows are shown in Fig. 6.

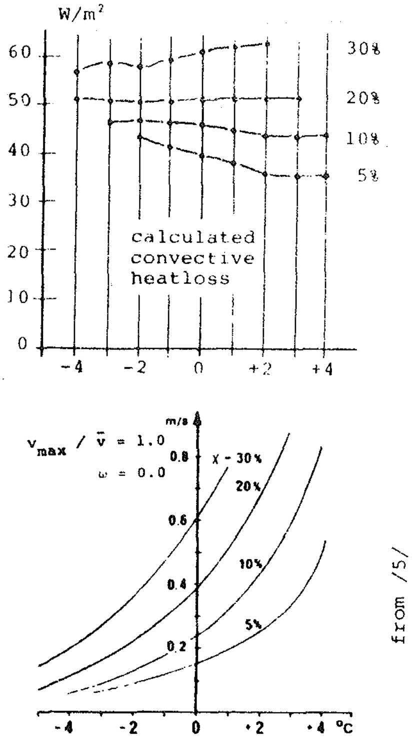

Fig. 6 - The calculated convective heat loss from the human skin exposed to different combinations of a smooth air velocity and a corresponding local air temperature. There seems to be a good correlation between the heatflow and the expected degree of discomfort

It will be seen that the heat flow is almost independent of the actual combination of local air temperature and velocity. This indicates that it is the magnitude of the heat flow which determines the extent to which draught feels uncomfortable.

Especially interesting are the results in /5/ which indicate the significant influence which the frequency of the air fluctuations has on the sensation of draught.

On the El-model the maximum heat flow through the receptors is determined, when the skin is exposed to a number of sine-shaped velocity changes with constant amplitude, but with different frequencies.

In Fig. 7 the result from /5/ is seen at the bottom and at the top the result from the El-model. The form of the two curves is almost identical, both having a maximum at about 0.5 Hz.

All the above-mentioned examples comfirm the theory that a local cooling of the body is uncomfortable when the heat flow through the skin exceeds a certain limit, or in other words, when the thermoreceptors send so many impulses to the brain that they cause discomfort.

As the nerve impulses from the individual receptors accumulate (see Fig. 2), a small heat flow through a large skin area will cause the same discomfort as a greater heat flow through a smaller area.

Assuming that it is the heat flow through the receptors which causes discomfort, and bearing in mind that these receptors are located under the skin surface and thus measure only heat conduction, and not radiation or convection, it is only to be expected that a greater heat flow caused by an increased radiation to cold surfaces will create the same degree of discomfort as those mentioned earlier for convective fields.

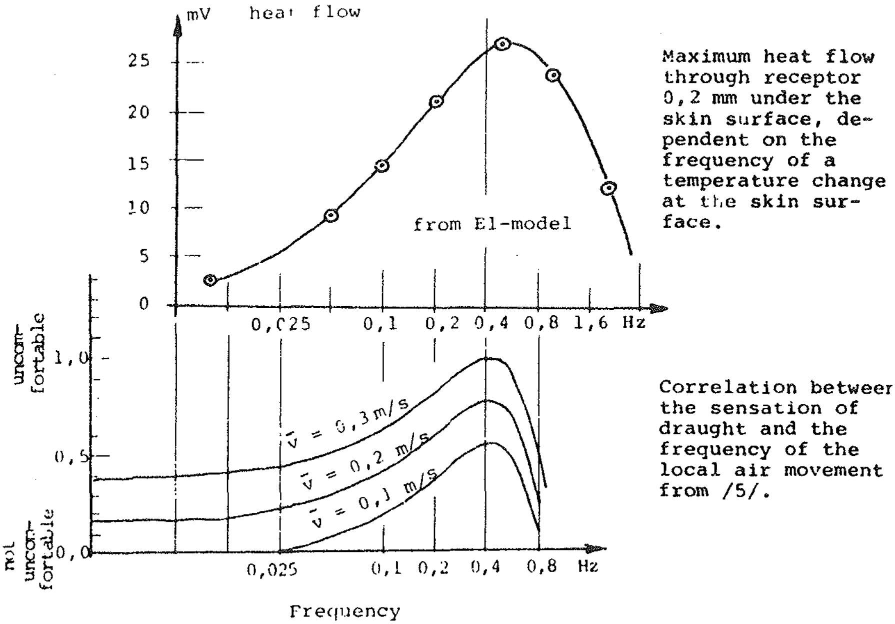

Fig. 7 - Comparison between heat flow through thermal receptors and the sensation of draught at different frequencies.

MEASURING INSTRUMENT

A logical consequence of the hypothesis outlined above would be a sensor which simulates the heat exchange between the skin and the environment at the place where discomfort may occur. If the heat flow from such a sensor becomes too great, local thermal discomfort can be expected.

The comfort limits for draught and thermal asymmetry found up to now are stated as either a maximum radiation temperature difference or a maximum permissible air velocity and not as a heat flow.

Therefore, a new instrument must be evolved for measuring the degree of discomfort caused by draught, taking into consideration all the four parameters mentioned in /5/. It would be desirable to include also the influence of increased radiation from the skin to cold surfaces.

Just as in the construction of the comfort meter /6/, the philosophy behind the development of this new instrument has been to simulate the thermal situation to be evaluated. In the comfort meter the sensor consists of a body which exchanges radiation- and convective heat with the environment in the same way as would a clothed standing or seated person in the same situation.

In analysing the local comfort problems of the body, the sensor must be made so that it statically and dynamically simulates the local heat exchange between the skin and the surroundings at the place where discomfort may occur.

In principle, such a sensor can consist of a surface element having the same thermal conductivity

heat capacity

surface temperature and

radiation properties

as the human skin.

The heat flow through such a surface will be a measure of the impulse frequency to the brain from the thermoreceptors in the skin, which the sensor should simulate.

Such a sensor (A in Fig. 8) can be a thin ceramic disc with a surface having the same radiation absorption range as the human skin. On the back of the disc there is a platinum film resistor of 100 Ω at $0^{\circ}C$. This resistor can be used both for heating the sensor and for controlling its temperature.

The disc is placed on a 10 mm insulating sheet which protects against undesirable heat loss. The effect introduced to the sensor is controlled by the platinum resistor, which by means of a measuring bridge, is connected to an air temperature sensor (B in Fig. 8) of the same material and resistance. In this way it is possible to keep the draught sensor (A) at a temperature which is always equal to the actual air temperature $+10^{\circ}C$. The $10^{\circ}C$ corresponds to a typical overtemperature of the naked skin at normal indoor temperatures ($23-24^{\circ}C$).

Function of the sensor

As mentioned above, there are four factors influencing thermal discomfort which can be caused by undesirable air movements. The sensor is constructed in such a way that the measurement of draught is performed with due consideration to all these factors.

1. The local air temperature compared to the temperature of the room air

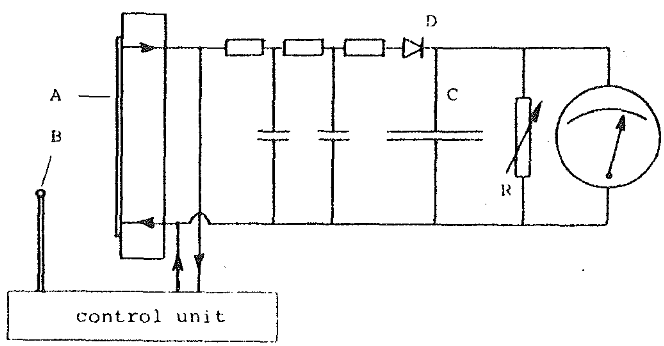

Fig. 8 - A simplied diagram showing the selection of the critical air velocity frequencies.

By supplying the thermistor (B), which measures the temperature of the room air, with a separate cable, it is possible to place it at a location where the air temperature is typical for the room, whereas the sensor (A) is placed where unpleasant draught is felt. If the air here is colder than at the thermistor, the discs will reach a temperature which is more than 10^0 higher than the ambient air and the effect will be increased.

2. The mean air velocity

As the disc has a constant overtemperature of 10^0C, the heat loss will depend only on the air movements around the sensor, and on the surface temperatures in the half-room which is "seen" by the disc. The sensor is calibrated in a room with surface temperatures equal to air temperature, i.e., similar conditions as those for the determination of the results in /5/. But if, for instance, the actual surface temperatures are lower than the air temperature, then the heat loss of the sensor, as with the human skin, will increase; this will cause exactly the same sensation of draught as a corresponding increase of the mean air velocity.

3. and 4. The velocity variation and its frequency

Fig. 8 shows how these important factors are included in the evaluation of the thermal discomfort which a particular air movement may be expected to cause.

The voltage over the heating element of the disc is led through an electric filter, through which voltage variations from very fast velocity changes (>1.0 Hz) cannot pass. Slower changes will penetrate and charge the condensor (C) through the diode (D) so that there will be a voltage over the pointer instrument greater than that corresponding to the average velocity. If the velocity changes are very slow (<<0.1 Hz), C will be discharged through the resistor (R). The deflection will become smaller and again approximate the mean velocity along the discs of the sensor.

The result is firstly, that the addition to the mean velocity shown by the pointer is proportional to the amplitude in the velocity variations, and secondly, that this addition is frequency-dependent according to the curves in Fig. 7.

A measuring unit for draught

There is as yet no unit which gives directly the degree of thermal discomfort as a result of draught, taking into consideration all the above-mentioned parameters.

In /5/ a number of diagrams are shown which for typical combinations indicate the mean air velocity which will cause 5, 10, 20 or 30% of persons to be thermally dissatisfied under otherwise optimal thermal conditions corresponding to PMV = 0 (6,7).

It is appropriate to introduce an equivalent air velocity (eav), i.e., a completely smooth velocity which in an isotherm environment will cause the same degree of thermal discomfort as the actual combination of the local air temperature, the radiation temperature, and the mean velocity as well as of the amplitude and frequency of possible velocity variations.

It is possible to measure directly the equivalent air velocity with the instrument described above, which is constructed to allow corrections of the measured mean velocity, converting this to the equivalent air velocity. According to /5/ the connection shown in Fig. 9 between

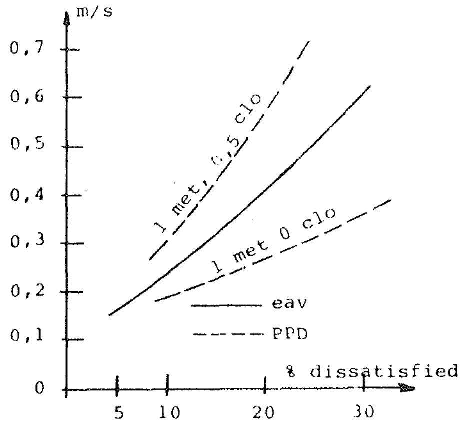

Fig. 9 - The connection between the equivalent air velocity and the expected percentage of dissatisfied. On the figure is also shown the predicted percentage of dissatisfied (PPD) as a result of a general increased air velocity.

the equivalent air velocity and the expected percentage of thermally dissatisfied persons is obtained from Fig. 6. Thus it is possible on the pointer instrument to indicate equivalent air velocities as well as percentages of thermally dissatisfied.

As the experimental material is still limited, the percentage scale is subject to a degree of uncertainty. The scale for equivalent velocity is more certain as it is based not only on climate chamber experiments, but also on the above-mentioned relation between the heat flow through, and nerve impulses from, the thermoreceptors of the skin.

Conclusion

Observations seem to show that thermal discomfort caused by local cooling of the human body is a result of an increased heat flow through the thermal receptors in the skin area exposed to this cooling. The discomfort may be caused by an increased radiation- or convection heat loss, or by a combination of the two. It would be advantageous, therefore, to have an instrument capable of simulating the human skin and of measuring the actual heat flow and its variations.

Before the hypothesis outlined in this paper can be accepted, further climate chamber experiments are needed. In such experiments, the test person should be exposed to different local thermal loads caused by both pure radiation and pure convection and by different combinations of these two typical reasons for heat loss, the purpose being to find a statistically significant correlation between the expected percentage of thermally dissatisfied and the heat flow through the skin.

When this correlation is known, it will be simple to adjust the instrument described above to a direct measuring of the expected degree of thermal discomfort caused by draught and/or radiation in a given environment. Until then, however, the equivalent air velocity is the most appropriate unit for describing correctly the expected local thermal discomfort.

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LES LIMITES DU COURANT D'AIR ET DES RADIATION ASYMETRIQUES EN RELATION AU CONFORT THERMIQUE DES PERSONNES:

RESUME : Les investigations en cours en plusieurs pays démontrent qu'après le bruit, le courant d'air est la cause la plus fréquente des plaintes de l'environnement du travail.

Au cours des années dernières des investigations ont été effectuées afin de trouver des limites acceptables des mouvements de l'air dans les zones de stationnement, de la même manière l'influence des champs des radiations asymétriques sur le confort thermique a été investigé.

Dans ce tirage à part nous cherchons de mettre en relation les résultats de ces investigations avec la sensation humaine vis-à-vis la température telle qu'elle est décrite par bon nombre de physiologues de monde entier. Cela ce fait en simulant la peau huamine et son appareil sensoriel par l'intermédiaire d'un model analogue électrique. De ce fait il apparaît que plusieurs résultats empiriques peuvent se manifester en une seule expression indiquant les limites du courant d'air et de la radiation en relation au dégré du confort thermique.

Finalement nous avons esquissé un instrument de mesure capable de mesurer si ces limites sont dépassés.