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WHY LOW AIR VELOCITIES MAY CAUSE THERMAL DISCOMFORT?

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Abstract

In this paper a hypothesis is set up for explaining the discrepancy between the relatively high acceptable air velocities found during many earlier climate chamber tests, and the much lower acceptable velocities found under many practical circumstances. A thermal-electrical analog model of the human skin including thermal receptors has been developed. The model is based on the similarity of the mathematical equations describing thermal and electrical conduction. The air velocity fluctuations which test persons have been exposed to in a climatic chamber was recorded on magnatic tape. It is now possible to impress this air velocity field on the analog model and measure the output from the thermal receptor and later to impress the constant air velocity which will cause the same mean output from the receptors. The comparison between this velocity and the actual mean air velocity measured in the climatic chamber, and the votes from the test persons form a basis for the hypothesis.

Introduction

Draught is one of the most frequent reasons for complaints of the indoor invironment. This is surprising because most of the earlier investigations done with test persons in climatic chambers seem to show that people can accept considerable air velocity as long as the operative temperature is increased to a level corresponding to an unchanged degree of general thermal comfort.

During each of these tests people have been exposed to a uniform air velocity, constant in both size, direction and temperature. In daily life such an air velocity seldom occur. Recent investigations carried out under more typical conditions show that people are considerably more sensitive to draught from a certain air velocity when this is fluctuating than when it is uniform.

In this paper a hypothesis is set up explaning why fluctuating air flow is felt more uncomfortable than constant air flow.

Physiology - Thermal Receptors in the Skin

Hensel (1) has studied and described the reaction of the skin exposed to different thermal impacts. He determined nerve impulse frequencies from a single thermoreceptor when skin was exposed to a transient thermal impact (Fig. 1). Fig. 2 shows another example from (1) 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 impact increases with the size of the exposed skin area. But which physical parameter determines this frequency?

In order to investigate this, an analysis of some typical and known connections between thermal skin impacts and the resultant nerve inpulse frequencies were studied on an electrical analog computer (3).

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.

Three examples of man's response to his thermal environment reported in the literature have been studied applying the electrical model.

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

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. 4b 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 between the shapes of the curves in Fig. 4a and 4b.

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

Hensel (2) has performed numerous experiments to find a possible connection between the rate of 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.

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.

C. Fanger and Pedersen (4) have exposed more than one hundred persons to uniform and fluctuating air velocities with different amplitudes and frequencies. They found an interesting correlation Fig. 6 between the sensation of draught and the frequency of the air movement.

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. 6 the result from (4) is seen at the bottom and at the top the result from the El-model. The shapes of the two curves are almost identical, both having a maximum at about 0.5 Hz.

All the above-mentioned examples confirm 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.

Measurements

In a climatic chamber 100 subjects were exposed to velocities with fluctuations as they occur in ventilated spaces in practice (5). Close to each subject the air velocity was measured with a DISA55R48 probe and recorded on a Brüel and Kjær tape recorder, type 7003. It was now possible to expose the electrical skin model to the same impact from the air velocity as the subjects. The output from the thermoreceptor was recorded and integrated during each measuring period (10 min.) on a Kipp & Zonen recorder, type BD12. Then a constant voltage was impressed on the model and it was possible, after measuring the corresponding output from the receptor, to calculate the uniform air velocity which would give the same output from the thermal receptors as the actual fluctuating air velocity.

In table 1 is shown, for five air velocities, the integrated mean air velocity during 10 minutes and the constant air velocity which would cause the same output from the thermal receptors. The given values are mean values of three different tests all recorded with an air temperature of 23°C in the climatic chamber. On Fig. (7) is shown the constant air velocity which would cause the same heat on the thermal receptors and thereby - this is the hypothesis - the same sensation of draught as the actual fluctuating air velocities he was exposed to in the climatic chamber.

Discussion

Earlier investigations specify rather high acceptable air velocities in occupied spaces. Nevins (6) found that 0.35 m/s would only cause 20% dissatisfied. McInture (7) explains that up to 0.35 m/s the comfort mean vote will still be neutral but the vote ranges are wider than for lower air velocities. New investigations by Fanger and Pedersen (4), and by Christensen et al (5) where subjects have been exposed to fluctuating air velocities, show significant lower limits for acceptable mean air velocities. On Fig. 6 is shown the influence of the frequency on the sensation of discomfort, and on Fig. 8 is seen the correlation between mean air velocity and percent dissatisfied at three different temperature levels. At an air temperature of 23°C and air velocity of only 0.21 m/s corresponds to 20% dissatisfied. At 20°C the same limit is reached at only 0.15 m/s. In the new ISO standard 7730 for moderate thermal environment is given a limit at 0.15 m/s which was expected to correspond to 5% dissatisfied. Because of the fluctuating air velocity the percentage seems to be significantly higher in typical indoor environments.

On the same figure is indicated the constant air velocity which - if the hypothesis is valid - may cause the same percentage of dissatisfied. For 23°C we find an equivalent constant air velocity of 0.38 m/s for 20% dissatisfied. This is in good agreement with Nevins' 0.35 m/s and also with Pedersen (8) who found the speed limit for 20% dissatisfied to be 0.4 m/s for a uniform air velocity.

The sensation of draught - or local thermal discomfort - may be caused by a combination of increased radiant and convective heat losses. The thermal receptors in the skin sense heat flow through the skin, and they are unable to distinguish between radiant and convective heat losses. The only reason for the higher sensitivity to convective than to radiant heat loss must be that the first one vary in time fluctuations while the second is constant.

Because of the high human sensitivity to convective draught, a sensitivity which is only partly based on the general heat balance or comfort equation, it is important to keep the air velocity in occupied spaces low and as constant as possible during the heating season. Otherwise the occupants will increase the room temperature. In order to compensate for the sensation of draught they may prefer a PMV-value higher than zero. This is energy consuming. One degree higher temperature costs typically 10% more energy and money.

To measure the local thermal discomfort there is a need for an instrument which is able to simulate the human skin thermally, and to measure the actual heat flow and its variation. Based on the presented hypothesis - such an instrument should be able to measure the expected degree of local thermal discomfort directly.

Conclusion

The human sensitivity to low air velocities seems to be caused by fluctuation of the air movement. A hypothesis has been lined out which indicates that the high sensitivity is a result of periodically high outputs from the thermal receptors to the brain caused by a corresponding high heat flow through this receptor following the moments of highest air velocity.

The hypothesis explains physiological measurements and human responses to uniform as well as fluctuating air movements.

On the basis of the hypothesis it may be possible to design a sensor which is able to measure the expected degree of local thermal discomfort taking both radiant heat loss as well as convective heat loss from constant or fluctuating air movements into account.

References

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Fig. 1 The variation of the impulse frequency from a single cold receptor as a function of the skin temperature from (1).

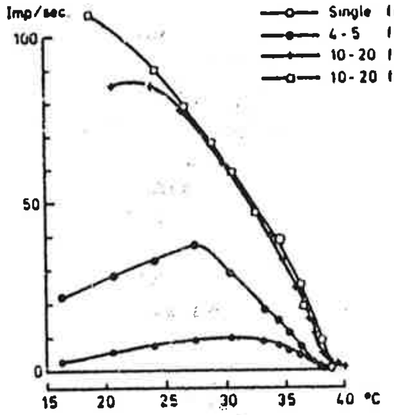

Fig. 2 Total impulse frequency of the steady discharge in different preparations of the cat lingual nerve as a function of the temperature of the tongue surface from (1).

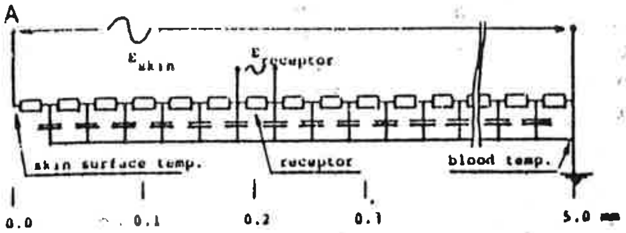

Fig. 3 Electrical analog model of the outer 5 mm of the human skin. Thermal conductivity 0.33 W/mK heat capacity 3.35 J/Kcm^3.

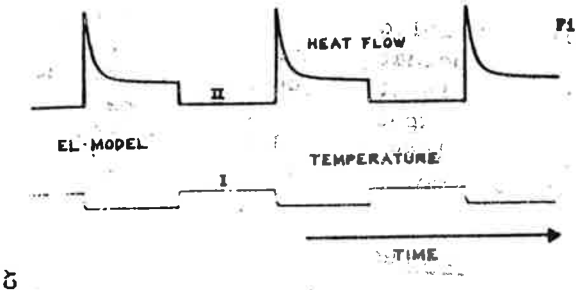

Fig. 4a A sudden temperature change in the skin surface is in the el-model simulated by suddenly changing the voltage in point A on fig. 3. The change is recorded by line I. The corresponding Voltage over the receptor is recorded by line II, which at the same time indicates the heat flow through the thermoreceptor.

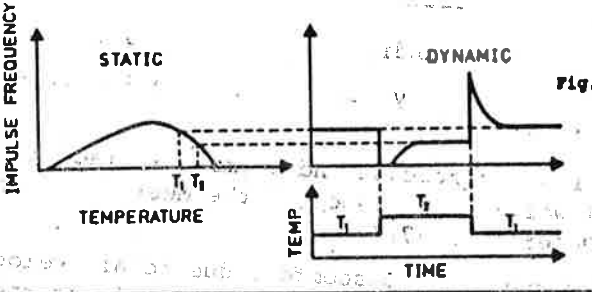

Fig. 4b Response from single cold receptor to constant temperature (left) and to rapid temperature changes (right).

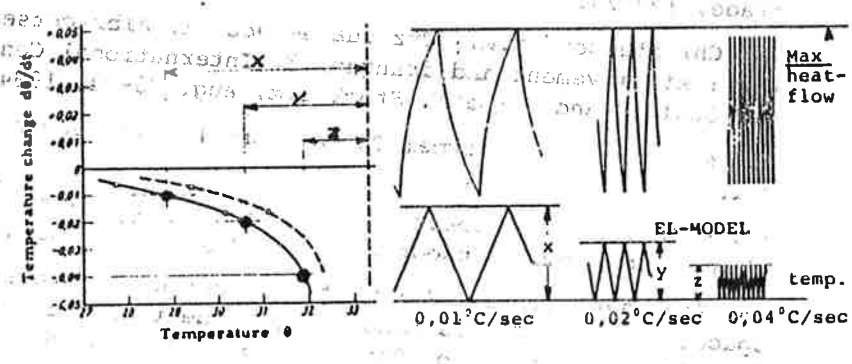

Fig. 5 Left figure: the correlation between the speed of temperature changes and the deviation from neutral temperature where cold is felt.
Right figure: the found deviation is put into the el-model as triangular voltage with corresponding change of speed. It will be seen that

Actual mean air velocity m/s	Equivalent air velocity m/s
0.10	0.24
0.15	0.30
0.22	0.36
0.29	0.45
0.40	0.60

Table 1. Result of measurement on electrical analog skin model. The equivalent air velocity is the constant air velocity which will cause the same impulse frequency from the thermal receptor to the brain as the actual fluctuating air velocity. Negative heat flow is cut off before integration of heat flow during each measuring period. Each number is a mean of three 10 minute periods all from tests with 23°C in a climate chamber.

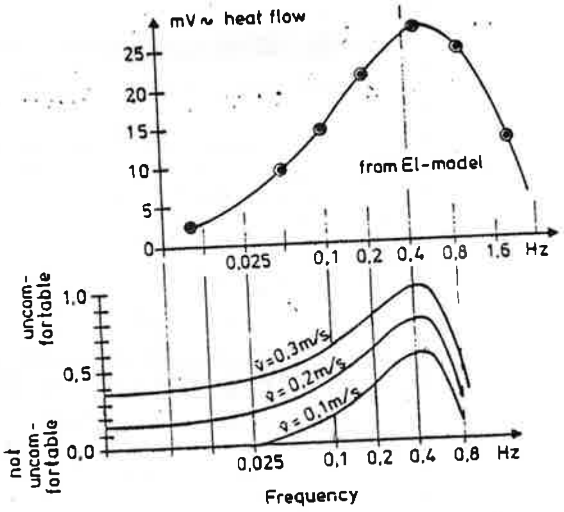

Fig. 6 Comparison between maximum heat flow through thermal receptor and the sensation of draught at different frequencies of fluctuating air movements from (8).

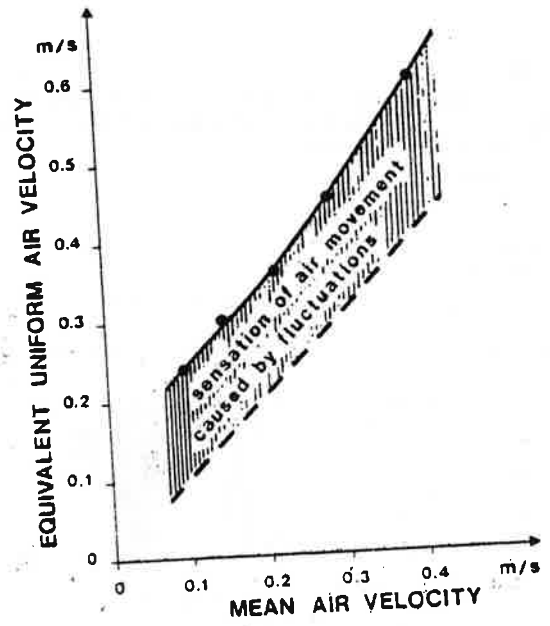

Fig. 7 Correlation between the actual mean air velocity and the uniform air velocity expected to cause the same sensation of draught as the actual fluctuating air air movement, from table 1.

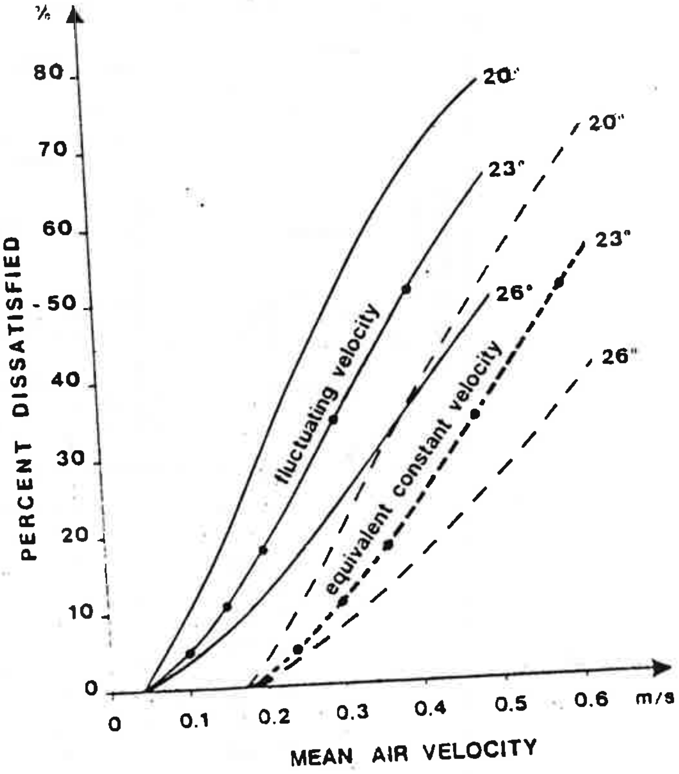

Fig. 8 Correlation between mean air velocity and percent dissatisfied at three temperature levels, curves from (5). The values from table 1 is plotted on the figure and forms the broken line for the equivalent air velocity which may cause the same percentage of dissatisfied at 23°C, right curve.