THERMAL INSULATION LABORATORY
TECHNICAL UNIVERSITY OF DENMARK

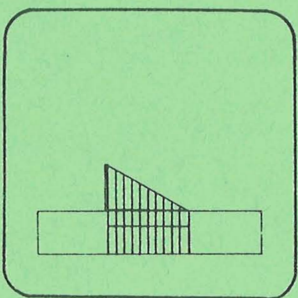
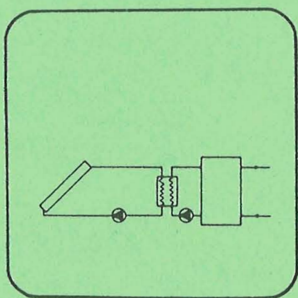
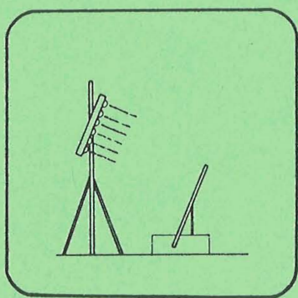
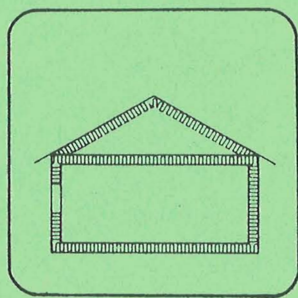
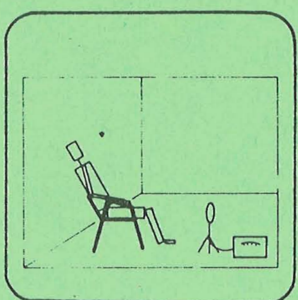
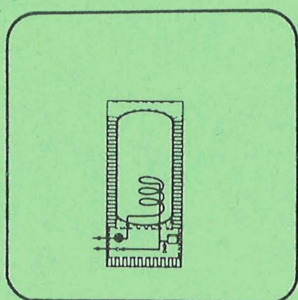
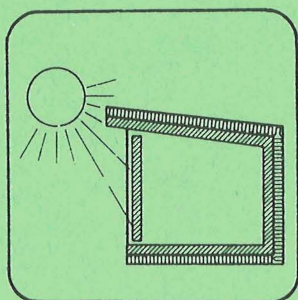
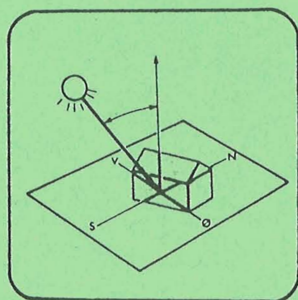
ASHRAE. Transactions, Vol. 86, Part 1

DEFINITION AND MEASUREMENT OF LOCAL THERMAL DISCOMFORT PARAMETERS

THOMAS LUND MADSEN

Report No. 100

February 1980

No. 2555

DEFINITION AND MEASUREMENT OF LOCAL THERMAL DISCOMFORT PARAMETERS

THOMAS LUND MADSEN

INTRODUCTION

The primary and most important requirement which has to be fulfilled for sustaining thermal comfort in a given environment is that the heat balance of a human being should be acceptable. In other words, the balance between the heat produced by the body and the heat loss to the surroundings should be maintained at a suitable skin temperature.

The extent to which it is possible to maintain this heat balance in a given environment can be measured using the Thermal Comfort Meter described in Ref 1 and 2.

This requirement is not always sufficient, however. There should also be an absence of large local thermal asymmetries, or gradients, as these may cause discomfort of some parts of the human body.

A number of climatic chamber tests (3,4,5,6) have shown that human beings will tolerate appriciably asymmetrical thermal fields. Nevertheless it is common experience that people often complain of undesirable local cooling in everyday environments. This conflict probably arises because the human subjects are, as a rule, kept in overall thermal comfort during such climate chamber tests where they are exposed to asymmetrical thermal fields. One exception to this rule is Chrenco (7), who did not compensate for an increased ceiling temperature by reducing other temperatures. He did indeed find considerably lower limits for the acceptable ceiling temperature. Cabanac (8) states that subjects who generally feel slightly cool will be more sensitive to an increased local cooling.

When it is necessary to implement a general reduction of the indoor temperature for reasons of energy conservation, there will be an increase in the number of people in or below the cold part of the comfort zone. It is important for the overall comfort of such people that local thermal discomfort caused by asymmetrical radiation fields or unwanted air movements are avoided. In this paper local discomfort parameters will be discussed, and an instrument will be described which has been specially developed for measuring them.

PHYSIOLOGICAL BACKGROUND

According to Hensel (9,10,11) the experience of local thermal discomfort is a complicated physiological phenomenon which depends on both the deep body thermal receptors and the thermal receptors in the exposed skin area. Benzinger states in Ref 12 that thermal discomfort on the cold side is perceived mainly by the thermal receptors of the skin, whereas thermal discomfort on the hot side is determined mainly by the deep body receptors. This view is born out by the fact

Thomas Lund Madsen, M.Sc., Associate Professor, Thermal Insulation Laboratory, Technical University of Denmark, DK-2800 Lyngby, Denmark.

that most complaints of local thermal discomfort are caused by local cooling. Only these will be dealt with in this paper.

Fig. 1, from Ref 9 shows how a sudden fall in skin temperature from T_2 to T_1 causes a short, abrupt rise in the impulse frequency from a receptor exposed to it. The frequency falls again gradually, and stabilizes at a level corresponding to the new skin temperature. From Fig. 2 it will be seen that during steady-state conditions the impulse frequency is almost proportional to the skin temperature change from the Zero-value which is about 38°C. Furthermore it is apparent from Fig. 2 that the impulses from individual receptors are added. This explains why the thermal discomfort, resulting from a local cold influence, will increase with the size of the cooled skin area.

In Ref 13, an electrical analogue model of the outermost 5 mm of the human skin was used to indicate that the heat flow (or temperature gradient) through the cold receptors of the skin may be related to the subjective sensation of cold in a given area of skin.

In the present state of knowledge it is, however, scarcely possible to use this heat flow as an indicator of the level of thermal discomfort. This is because, as mentioned above, firstly the degree of local discomfort depends also on the general level of comfort of the subject, and secondly the local thermal discomfort resulting from a given cooling influence depends on the size of the exposed skin area.

It is, however, useful to know this connection when one is trying to evaluate which physical parameters are best suited for the indication of the expected local thermal discomfort in given surroundings.

LOCAL THERMAL-DISCOMFORT PARAMETERS

Draft is the parameter which is often mentioned when the context is local thermal discomfort. The latter can, however, also be caused by increased radiation heat loss to large, cold surfaces. In practice a combination of these two effects will often occur. It is therefore unfortunate that hitherto comfort limits have been laid down only for each of these two parameters singly, none having been provided for various combinations.

Draft Parameters

Draft may be defined as an unwanted local cooling of the human body caused by air movement. In the standards published in different countries, widely varying limits are laid down for air velocities, but very few experimental studies relating to drafts have been reported in the literature. In a recent experimental study (15) it was demonstrated that the sensation of draft depends on the following four factors:

1. The mean air velocity;
2. The maximum air velocity;
3. The frequencies of velocity fluctuations;
4. The difference between the local air flow temperature and the air temperature corresponding to general thermal comfort.

No index has been given in Ref 15 for the determination of the degree of thermal discomfort caused by draft. Instead, combinations of the four factors have been given, predicted to cause 5, 10, 20 and 30% of the people to feel draft.

An explanation of this complicated relation is given in Ref 13. Here it is demonstrated that the parameter combination, which in Ref 15 were found to cause thermal dissatisfaction of most subjects, were those which will cause large heat flows through the exposed skin areas. In Fig. 3 the relation between discomfort ratings and the frequency of the air variation found in Ref 15 is shown at the bottom, and the corresponding connection between the calculated maximum heat flow through the cutaneous thermal receptors and the frequency of air variations in Ref 13 is shown above. In Fig. 4 another comparison is shown between heat flow through the skin and local thermal discomfort. At the bottom of the figure an example from Ref 15 is illustrated. It is shown how the value of local smooth air velocity, which will give rise to thermal discomfort for 5,10, 20 and 30% of the people , varies according to the difference between local air temperature and the air temperature in general thermal comfort. The corresponding calculated heat flows through the skin are shown at the top. It will be apparent that at a given discomfort level the heat flow is almost independent of the actual combination of local air temperature and velocity.

Both these comparisons confirm the hypothesis that the heat flow through the skin is a parameter which is well correlated with the degree of local thermal discomfort.

There would seem to be a case for a new index for draft. This index, the equivalent air velocity eav, is defined as follows: That completely uniform air velocity which, in an isothermal environment, will cause the same degree of thermal discomfort as the actual combination of the local air temperature and mean velocity, as well as of the amplitude and frequency of any velocity variations. In this form the eav is difficult to determine in practice. If, however, in accordance with the hypothesis from Ref 13, one substitutes "maximum heat flow through the exposed skin area" for "degree of thermal discomfort," a physical parameter is obtained which can be measured directly.

Note that using the heat flow for the comparison of two thermal influences obviates the need to know both the general condition of thermal comfort and the size of the affected skin area, as these are the same in both situations.

Thermal Asymmetry

As a measure of the degree of thermal asymmetry in a radiation field (16), the radiant temperature asymmetry Δt_{pr} is often used, and is defined as the difference between the plane radiant temperature on the two sides of a flat element. (See nomenclature).

Thermal asymmetry can also, as mentioned before, be caused by air movements. In practice the most common situation is a combination of radiant and convective asymmetry. If these two asymmetries partly neutralize each other, it is likely that the degree of thermal discomfort will diminish; If they augment each other, it will increase. This idea suggests the introduction of another parameter, analogous to Δt_{pr} but combining the sum of radiant and convective asymmetries. This new term will be called the equivalent temperature asymmetry Δt_{pe}. It is defined as the difference between the equivalent temperatures on the two sides of a plane element.

This definition fits in excellently with the heat flow hypothesis in Ref 13 when it is remembered that the equivalent temperature is defined as the common value of air temperature and mean radiant temperature, which results in the same dry heat loss from a person in still air as that produced by the actual combination of airtemperature, mean air velocity and mean radiant temperature.

Δt_{pe} provides an immediate expression of the difference in heat flows through two skin elements oriented in opposite direction on a given person. The influence of points 2 and 3 of the draft criterion from Ref 15 has not yet been incorporated in this definition. The reason for this is that these points do not influence the dry heat loss, but only the discomfort which follows it.

Δt_{pe} is well suited to use as a limiting criterion for permissible asymmetry in the thermal field. It cannot be used directly, however, for an absolute evaluation of the expected level of thermal discomfort in a given situation, as the latter is dependent in addition on the following variables:

1. The heat balance between the subject and the surroundings, the PMV value (14);
2. The subject's clothing (clo value);
3. The subject's activity-level;
4. The direction of Δt_{pe} in relation to the subject;

At present no data exist which make it possible to state directly the expected level of thermal discomfort resulting from a given value of Δt_{pe} in relation to all these four parameters.

A NEW MEASURING INSTRUMENT

As with the thermal comfort meter described in Ref 1, the principle behind the development of the new measuring instrument to be described has been that of simulating the thermal situation to be investigated. In the case of the comfort meter, the sensor is a body which exchanges heat with the surroundings by convection and radiation in the same way as a fully dressed standing or seated person would in the same thermal situation Fig. 5.

A corresponding sensor for the determination of the expected level of local thermal discomfort must in principle consist of a flat element which has the same surface temperature and radiation properties as the unclothed human skin. It is required to have the same thermal conductivity and heat capacity as the outmost 0.2 mm of the skin. When a platinum film resistance (A_1) is placed behind this element and covered by a sheet of minimal thermal conductivity and capacity, the result is a probe which in principle is well suited to the evaluating of local thermal discomfort. (See Fig. 5 and 6). It is possible by means of A_1 to maintain the surface temperature of the probe at a level which corresponds to the skin temperature in any thermal comfort situation. Measurement of the power needed to maintain this temperature provides a direct indication of the heat flow at the position of the equivalent thermal receptor.

This sensor may be used directly for measuring the equivalent temperature of the surroundings in relation to a planar element. This requires only a calibration of the probe for its heat loss at certain known values of the equivalent temperature in isothermal surroundings and still air.

Measuring the Equivalent Temperature Asymmetry, Δt_{pe}

This parameter is defined as the difference between the equivalent temperatures on the two sides of a plane element. This condition may be achieved most simply by attaching another surface element with a platinum film resistance A_2 on the opposite side of the insulating sheet. The measured difference between the equivalent temperatures determined from the heat losses from A_1 and A_2 is the Δt_{pe}.

Measuring the Equivalent Air Velocity, eav

The equivalent air velocity is determined solely from the convective heat loss from the skin. Accordingly, a sensor for measuring eav ought to have properties which render it insensitive to radiation from the surroundings. This may be achieved by covering the probe with a reflective layer, e.g. a layer of gold. A probe of this form will measure only the convective heat loss from the skin.

In the form described, the probe will consist of both radiation-absorbing and radiation-reflecting elements. Fig. 5 shows the original form of a practical functional probe. Similar placement of the elements on both sides of the probe will cause their thermal convection effects to cancel, and will also eliminate effects of air direction on the results of the measurement.

However, eav quantities only change in the convective heat loss caused by local air movements. It should therefore be measured in relation to the neutral air temperature of the surroundings, and not in relation to the comfort temperature of the skin. This is the reason why the probe arrangement in Fig. 5 and 6 incorporates an unheated platinum resistance B for measuring the actual air temperature, as well as an electronic control circuit to maintain all the planar elements at a constant temperature above that of the surrounding air when eav is being measured.

For the prototype of this new measuring instrument, this temperature difference was chosen to be 10 K. This corresponds to the typical amount by which the surface temperature of bare skin exceeds an indoor temperature of 22-24°C.

This probe is able to measure eav directly, taking proper account of all the four factors stated to be relevant to the sensation of draft in Ref 15. After the heat loss from A has been determined in isothermal surroundings with zero air velocity, corresponding to eav = 0, the mean air velocity can be determined by the measurement of the concurrent increase in heat loss from A when A and B are placed close together.

Placing B in the general temperature field enables the influence of the difference between the air-flow temperature and the general air temperature to be determined. If, for instance, the general temperature is greater than the air temperature at the position where A is measuring eav, then the difference in temperature between A and the surrounding air will be > 10deg. This itself would bring about an increased heat loss and therefore a positive eav.

The influence of possible changes in the air velocity, and their frequency, enter into the determination of eav, as shown in Fig. 6. Very fast frequencies, above 1 Hz, do not get through the probe disc and into A_1. The frequencies which do get through will cause a periodic increase in voltage across A_1. These voltage peaks will charge the capacitor C through the diode D. The indicating meter will accordingly register a greater eav value than the mean velocity. Very slow changes in velocity (much less than 0.1 Hz) will discharge C through the resistor R. The power will decrease, and again tend to the value corresponding to the mean velocity across the surface of the probe. Fig. 7 shows an example of how eav varies with the frequency of variation in velocity measured with the new instrument.

Measurement of Other Thermal Comfort Parameters

The shape of probe chosen enables it to be used directly to determine a number of other important thermal parameters.

The Air Temperature may be determined using B, and is read directly on the indicating meter.

The Plane Radiant Temperature, t_{pr} (16), or the directional mean radiant temperature, dmrt (17), is calculated by the instrument from the measured difference between the heat losses from the absorbing and reflecting surfaces on the same side of the probe. This difference constitutes the instantaneous radiant heat loss, but a correction needs to be made in the instrument to allow for the fact that neither the reflection nor the absorption of the elements is total.

The Radiant Temperature Asymmetry, Δt_{pr} (16)

This quantity can be evaluated directly as the difference between the two values which have been obtained for t_{pr}.

As mentioned previously, the Mean Air Velocity, mav, can be obtained if B is placed next to A and the convective heat loss from A_2 integrated in the instrument over a suitable time interval, e.g., 1 min. In this measurement it is necessary to make a correction if prt is greater or less than the air temperature. This is due to the fact that the plane elements used for measuring mav are not 100% reflecting.

Normally, a sphere is considered most suitable for omnidirectional air velocity measurement. Fig. 8 shows the measured relationship between the probe orientation relative to a specific uniform air movement, and the measured mean value of the velocity along the two sides of the probe. This result indicates that this probe can be used for measuring the mean air velocity with reasonable accuracy, even if the direction of the latter is variable or unknown.

The Mean Radiant Temperature, mrt

With the instrument described here the mean radiant temperature cannot be measured directly. It can, however, be found quickly as an average of the six t_{pr} values obtained by measuring with the sensor in three mutually perpendicular directions. Such a measurement is both quicker and more informative than a conventional measurement with a globe.

CONCLUSION

There still exists no available index or limit criteria for the local thermal effects which can directly give the expected degree of thermal discomfort. This is because in each of the investigations carried out up till now, the influence of only a single parameter on the comfort perception has been taken into account. Naturally the result has been that the comfort limit has been given as a maximum acceptable value of that specific parameter. In reality, the local thermal discomfort in most cases is caused by a combination of different thermal effects, and comfort limits should therefore be laid down (similar to the PMV index) relative to the person's expected subjective reaction under all normal possible combinations of local thermal effects.

Even today there are no standard measuring methods for determination of the degree of thermal asymmetry or draft. Neither are there any measuring instruments on the market which are particularly adapted for these measurements.

The measuring instrument described here is developed as an aid to fulfilling this need. Just as in the case of the comfort meter, the instrument has been constructed with the aim of simulating a person's heat exchange with the surroundings.

While the comfort meter takes into consideration the heat loss of a person as a whole, and hence of the central temperature perception, the discomfort analyzer aims at simulating a person's peripheral temperature perception.

There is still a need for a "coordinator" which can assimilate signals from the two instruments to obtain an absolute value which gives a person's overall perception of thermal environment. For such a "coordinator" to be constructed, more experimental results are required which can form the basis for establishing subjective comfort criteria for local thermal effects. Besides, further investigations are necessary to determine how different combinations of central and local thermal effects affect a person's perception of thermal comfort.

Until such investigations are available it is deemed that the parameters discussed here are the most suitable for characterizing a room's thermal condition.

NOMENCLATURE

Definitions of local thermal discomfort parameters:

DRAFT - is an unwanted local convective cooling of a person . The sensation of discomfort is dependent on:

1. The mean air velocity;
2. The maximum air velocity;
3. The frequencies of velocity variations;
4. The difference between the air flow temperature and the neutral temperature.

The equivalent air velocity, eav, is the completely uniform air velocity which, in an isotherm environment, will cause the same degree of thermal discomfort as the actual combination of the local air temperature and mean velocity as well as of the amplitude and frequency of any velocity variations.

THERMAL ASYMMETRY

The plane radiant temperature, t_{pr}, is the uniform temperature of a hemisphere which would provide the same radiant with a small plane element as in the real environment.

Radiant temperature asymmetry, Δt_{pr}, is the difference between the plane radiant temperature of two opposite sides of a small plane element.

The plane equivalent temperature, t_{pe}, is the common value of air temperature and plane radiant temperature which, at an air velocity nil, would provide the same dry heat loss from a small skin surface element as in the real environment.

The equivalent temperature asymmetry, Δt_{pe}, is the difference between the plane equivalent temperature of two opposite oriented small skin surface elements.

REFERENCES

1. Madsen, Thomas Lund, "Thermal Comfort Measurements", ASHRAE Trans., Vol. 82, Part 1, 1976.

2. ASHRAE HANDBOOK of Fundamentals 1977, "Measurement and Instruments",13.11.

3. McNall, P.E., Jr. and Biddison, R.E., "Thermal and Comfort Sensations of Sedentary Persons Exposed to Asymmetric Radiant Fields", ASHRAE Trans., Vol. 76, Part 1, 1970.

4. Olesen, S., Fanger, P.O., Jensen, P.B. and Nielsen, O.J., "Comfort Limits for Man Exposed to Asymmetric Thermal Radiation", Proceedings of the CIB. Commission W 45 (Human Requirement) Symposium: Thermal Comfort and Moderate Heat Stress, Building Research Station, Sept. 1972.

5. Østergaard J., Fanger, P.O., Olesen S. and Madsen, Th. L., "The Effect on Man's Comfort of a Uniform Air Flow from Different Directions", ASHRAE Trans., Vol. 80, Part 1, 1974.

6. Gagge A.P., Hardy J.D. and Rapp G.M., "Exploratory Study of Comfort for High Temperature Sources of Radiant Heat", ASHRAE Trans., Vol. 71, Part 2, 1965.

7. Chrenco, F.A., "Heated ceilings and Comfort", Journal of the Inst. of Heating and Ventilating Engineers, 20:375-396 and 21:145-154, 1953.

8. Cabanac, Michel, "Plaisir ou Deplaisir de la Sensation Thermique et Homeothermie", Physiology and Behaviour, 4. 1969.

9. Hensel H., "Temperature Receptors in the Skin"., in: Hardy J.D., Gagge A.P. and Strewijk (Eds), Physiological Behavioral Temperature Regulation, C.C. Thomas, 1970, p. 442, Springfield.

10. Hensel H. and Zotterman, Acta Physiol. Scandinavia 23, 291, 1951.

11. Hensel, H., "Thermoreception and Human Comfort", International Indoor Climate Symposium, Copenhagen, Aug.-Sept. 1978.

12. Benzinger, T.H., "The Physiological Basis for Thermal Comfort", International Indoor Climate Symposium, Copenhagen, Aug.-Sept. 1978.

13. Madsen, Thomas Lund, "Limits for Draught and Asymmetric Radiation in Relation to Human Thermal Well-Being", Meeting of Commission E1 of the International Institute of Refrigeration, Belgrade, 1977.

14. Fanger, P.O., Thermal Comfort, McGraw-Hill Book Co., New York, 1973.

15. Fanger, P.O. and Pedersen C.I.K., "Discomfort Due to Air Velocities in Spaces", Meeting of Commission E1 of the International Institute of Refrigeration, Belgrade, 1977.

16. McIntyre, D.A., "The Thermal Radiation Field", Building Science, Vol. 9, Pergamon Press, 1974.

17. Korsgaard, V., "Necessity of Using a Directional Mean Radiant Temperature to Describe the Thermal Conditions in Rooms", Heat. Pip. Air Condit. 21., 1949.

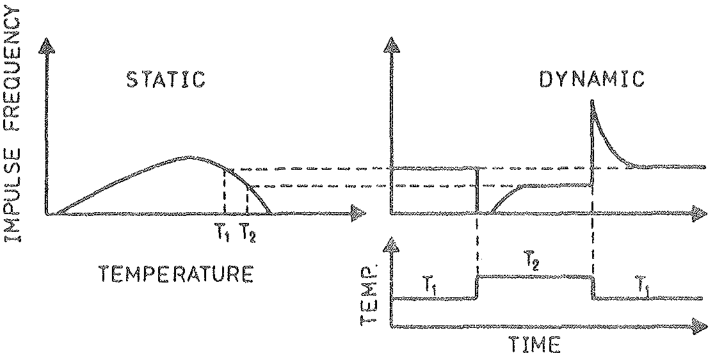


Fig. 1 Generalized scheme for responses of a single cold receptor to constant temperature (static response) and to rapid changes in temperature (dynamic response) (from Ref 9)

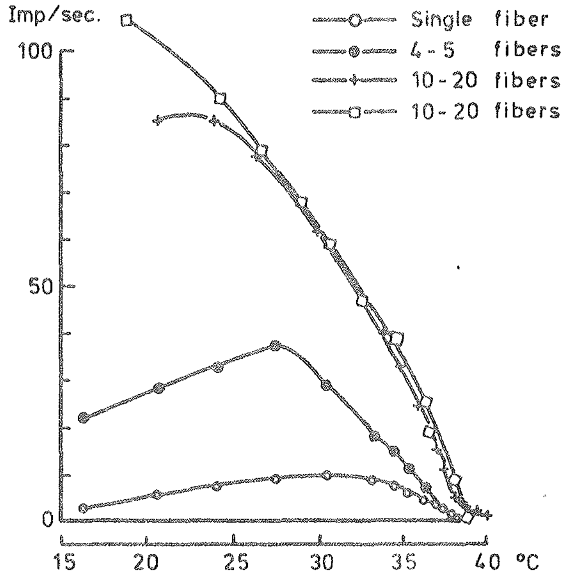


Fig. 2 Total impluse frequency of the steady discharge in different preparations of the cat lingual nerve as a function of the temperature of the tongue surface (from Ref 10)

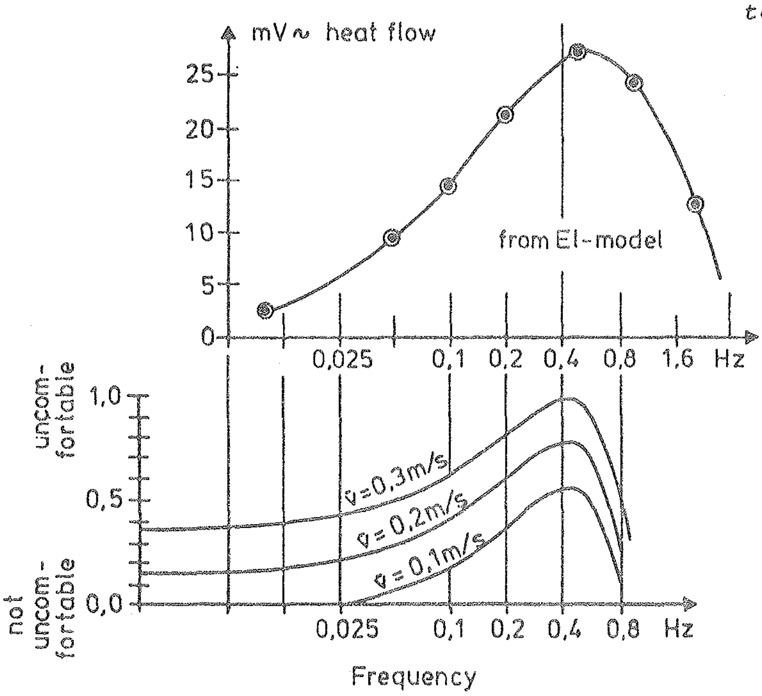


Fig. 3 Comparison between heat flow through thermal receptors and the sensation of discomfort at different frequencies of the velocity fluctuations:

Above is shown the maximum heat flow through receptor 0.2 mm under the skin surface, dependent on the frequency of a temperature change at the skin surface

Below is shown the correlation between the sensation of draft and the frequency of the local air movement (from Ref 15)

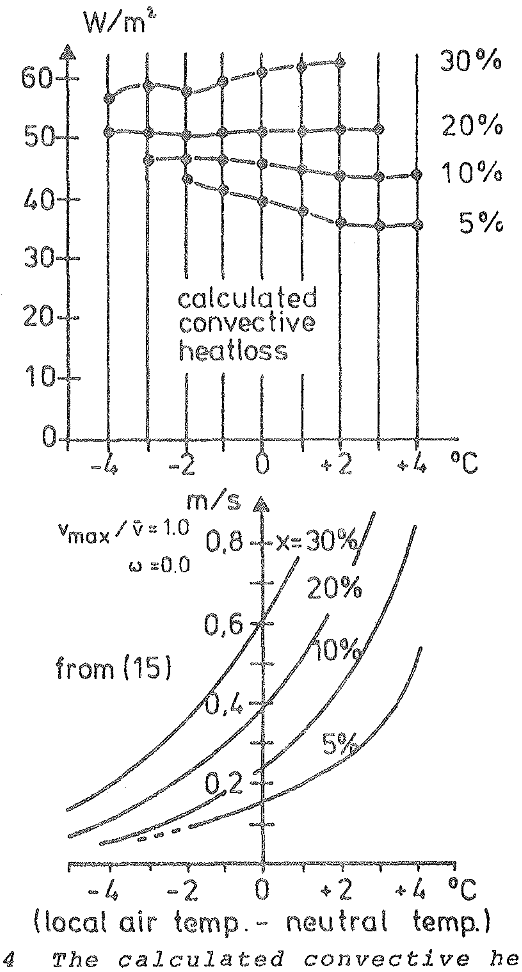


Fig. 4 The calculated convective heat loss from the human skin exposed to different combinations of a constant air velocity and a corresponding local air temperature. There seems to be a good correlation between the heat flow and the expected degree of discomfort from Ref 13)

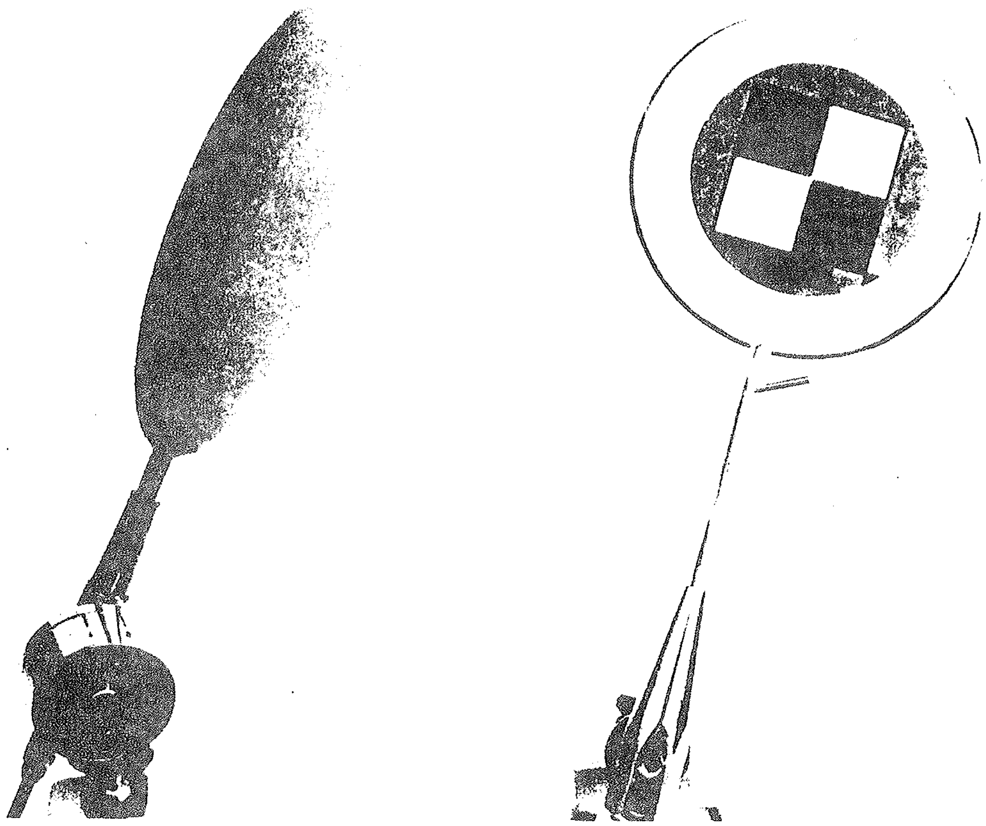


Fig. 5 Sensors for measurement of thermal discomfort: On the left is a sensor developed for measurement of the dry heat loss from the human body as a whole, and on the right is the new sensor for measuring draft and thermal asymmetry. Each side of the new sensor has 2 gold-plated and 2 black-painted elements, which are heated separately by a platinum resistance between the element and the insulating sheet.

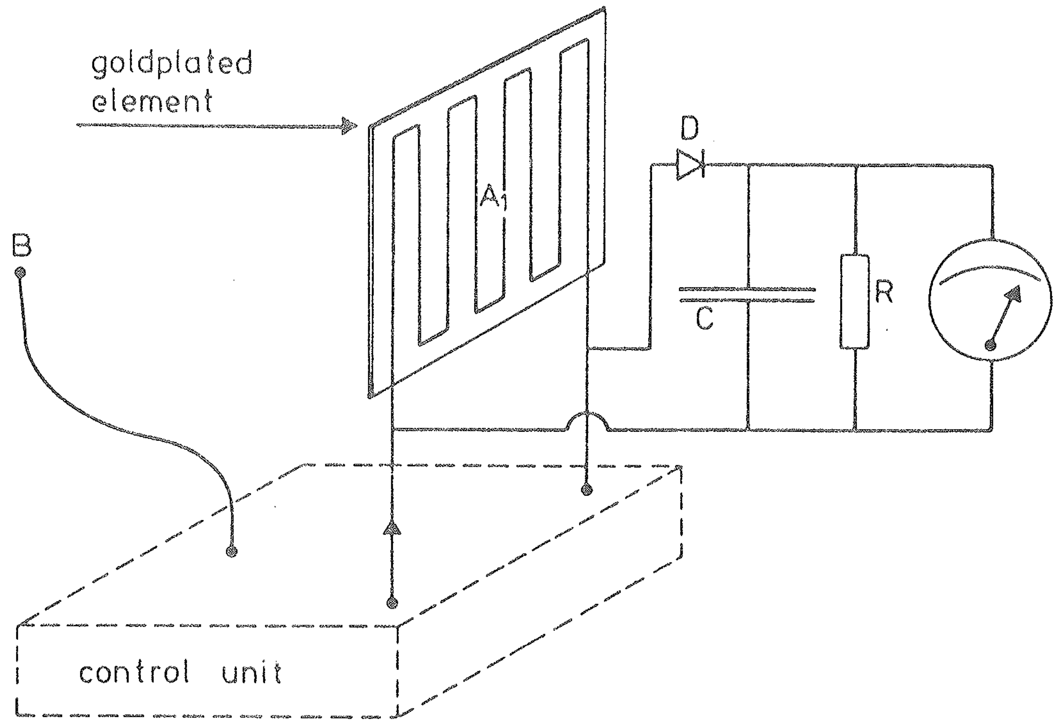


Fig. 6 A simplified diagram showing the selection of the critical air velocity frequencies from one of the gold-plated elements. The element has the same thermal properties as the outermost 0.2 mm of the human skin.

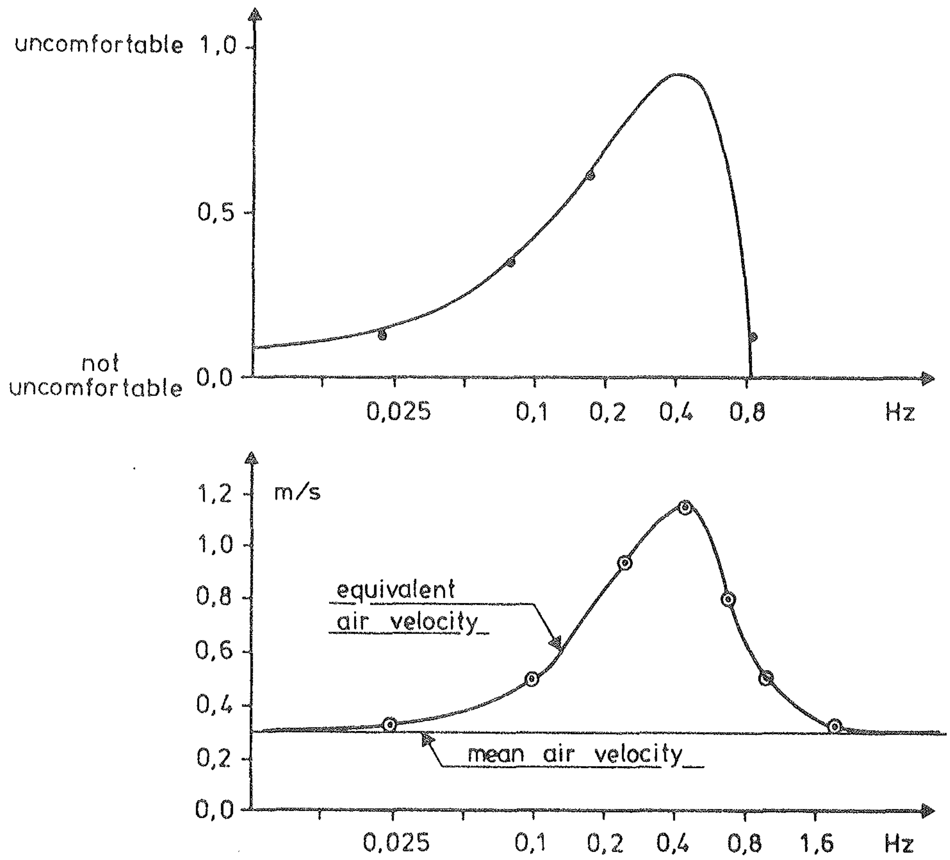


Fig. 7

At the top is shown the correlation between the sensation of draft and the frequency of the local air movement.

At the bottom is shown eav and mav measured simultaneously with the new instrument.

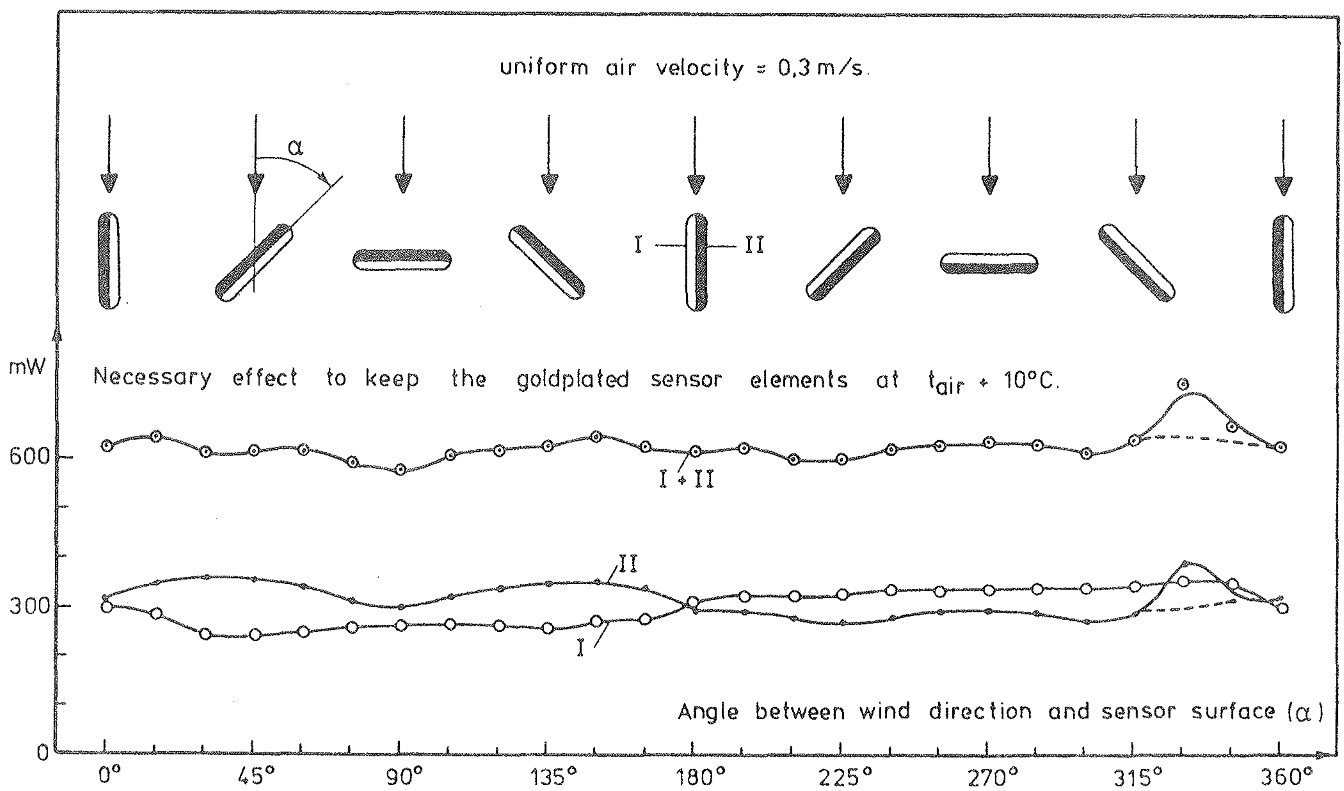


Fig. 8 The measured heat loss from the gold-plated sensor element in relation to the angle between the direction of a uniform airstream and the sensor surface. mav = 0.3 m/s.

DISCUSSION

JOEL JACKMAN, Eng., R&D, Puget Power, Bellevue, WA: Your study relates to sensible heat loss. Have you done any work with latent heat loss?

T.L. MADSEN: No. I have until now been interested in the comfort and the cold discomfort zone. This is - and it will especially be - the most common thermal situation in Scandinavia and, I think in many areas in the U.S. and Canada. And in the neutral as well as in the cold zone the latent heat loss is only of minor importance. Nevertheless, it is our intention to supply the comfort analyzer, described in my paper, with a sensor for measuring the relative humidity of the air and with an electronic circuit for calculating the partial water vapor pressure of the air from the measured values of the air temperature and relative humidity.

DAVID T. HARRJE, Sr. Res. Engr. & Lecturer, Princeton Univ., Princeton, NJ: Has this new thermal comfort probe been used to map out a room with regard to window and air flow influences on local discomfort?

MADSEN: The instrument I have presented here is the very first prototype and there are still some problems, mainly concerning the separation of the radiation output from the convective output, when the air velocity is fluctuating. But it has, in fact, been used for practical measurements in a hospital ward in a big, new Danish hospital where some of the patients in the beds close to the big window complained of draft. Our measurements gave no reason for this complaint, there were no air velocities nor radiation field which could give rise to any sensation of draft. We found that the only logical reason was the actual position of the air inlets which made the curtains move slightly in front of the patient. This slow but steady movement might give rise to a psychological sensation of draft for a person with nothing much to do. Compare with Dr. Rohles' paper *Temperature or Temperament* at the ASHRAE meeting.

R.F. GOLDMAN, Dir.-Military Ergonomics, U.S. Army Res. Inst. Environ. Med., Natick, MA: You resurrect the 1960's argument of Benzinger that central temperature was the key factor in heat discomfort. Most ASHRAE work on heat discomfort is based on the concept of percentage of wetted skin, as suggested originally by Gagge. Central temperature is only involved as a forcing function for sweating, while skin wetness is a function of the skin-to-air vapor pressure difference, clothing insulation and permeability, and the basic requirement for evaporative cooling.

MADSEN: As mentioned in my paper this only deals with local thermal comfort caused by cooling. When I mentioned Benzinger's statement the reason was to point out that local thermal discomfort is mostly a phenomenon which occurs in connection with or as a result of a general thermal discomfort to the cold and not to the warm side of the comfort zone. I think that sweating - which, as you mention, is forced by the central temperature sensation - is sensed as a more general discomfort than, for instance, a cold neck or cold feet.