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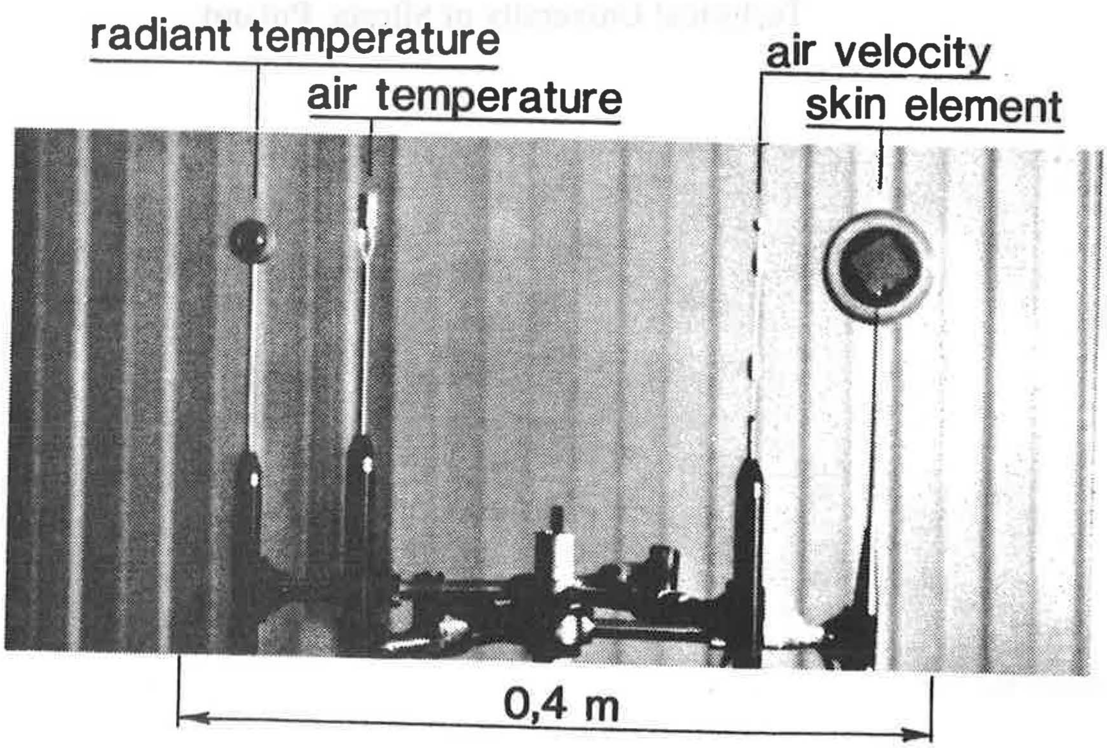
SUMMARY

Draught is not only a question of air velocity. Air temperature, turbulence intensity and radiation to cold surfaces but may also create the sensation of local discomfort called draught. A new transducer is developed, which simulates the heat loss from the human skin. This "skin" element is heated to a temperature in agreement with the most comfortable combination of skin temperature and heat loss. In the measuring instrument a microprocessor simulates thermally the outer five mm of the human skin including the cold thermal receptors and calculates a new index: the Percieved Heat Flux (PHF), which is the sensation of cold felt by the cold thermal receptors in the skin. This instrument is compared to results from new investigations in the field of draught and asymmetric radiation. The main result is a simple transfer function between the percieved heat flux measured by means of the instrument and the expected percentage of discomfort calculated from a new draught risk equation after measurement of all relevant parameters using conventional instrumentation.



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Introduction

The degree of general Thermal Comfort according to ISO7730 (1) can be measured directly using a Thermal Comfort Meter (2) or it can be calculated from measured values.

No instrument is to be found on the market by means of which it is possible, in a similar direct manner, to measure the local thermal discomfort caused by draught and/or increased radiant heat loss.

There is a considerable need for an instrument of this kind mainly because a disagreement seems to exist between ISO7730 and the daily experience in modern buildings.

In ISO7730 a limit is given for the mean air velocity at 0.15 m/s under winter conditions and at 0.25 m/s under summer conditions, these values were expected to correspond to <5% thermally dissatisfied. Investigation (3) and (4), carried out in typical environments, do not show 5% but 15 - 20% dissatisfied even if the ISO7730 is observed.

The reason for this disagreement is that air movements in rooms are normally turbulent and not laminar as in climatic test chambers. This turbulence creates an increased convective heat transfer coefficient (5) and even more important, the turbulence creates a fluctuation in the heat flow through the cold thermal receptors in the human skin and thereby an increased sensation of cold (6).

The increased sensation of cold can also be caused by a low plane radiant temperature for instance where the skin is facing a cold window. The thermal receptors are placed under the skin surface and will, therefore, have no sensation for convection nor radiation but for conduction or, more correct, heat flux.

Consequently, this new instrument is designed to measure the instantaneous heat loss from a small plane element with similar radiant properties as the human skin, and kept at similar temperatures as the human skin in a thermal comfort situation and sedentary.

Construction of the Skin Element

The skin element is shown in fig. 1. It consists of two thin ceramic plates (25 x 25 mm^2) one on each side of a 5 mm insulation layer. There is a platinum film resistance (PT100) at the top of each plate. Each resistor is part of a constant temperature bridge, which controls the voltage to the sensor to maintain a constant surface temperature of each sensor plate. The temperature has been chosen to be 34°C, the reason for this choice is that a sensation of draught is, as a rule, related to people with low activity levels and the optimum mean skin temperature for an activity of 1 met is according to (7) 34.1°C. The skin element is painted to have a similar emmissivity of long and short wave radiation as the human skin.

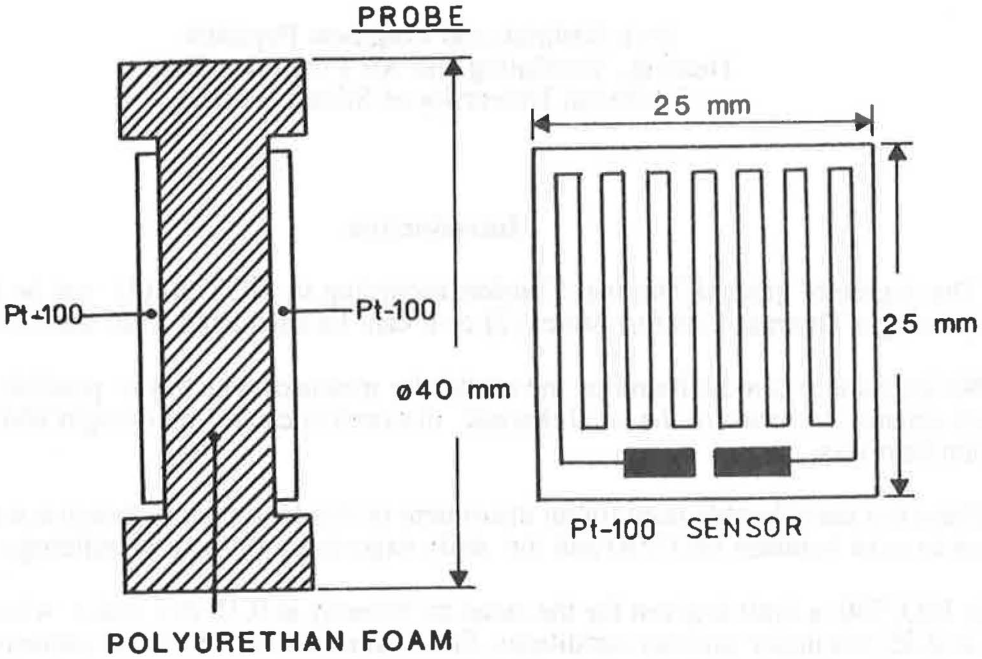

Fig. 1. Skin element.

Construction of the Instrument

The main idea of this invention is to simulate the human sensation of local heat loss. In (6) and (8) it is shown that the high sensitivity to draught can be explained by the unpleasant peaks of signal frequencies from cold receptors to the brain following each moment of high air velocity. This means that the sensation of draught is not only a result of an increased convective heat flux, but also caused by the variation of the heat flux through the skin. It is, consequently, not sufficient to measure the Mean Heat Flux (MHF) from the skin element. It is necessary to simulate the thermal fluctuation in the human skin and thus to be able to observe the cold receptors reaction to a turbulent air velocity. The simulation is made in a microprocessor where the electical signals received from the skin element are transformed to a value called the Perceived Heat Flux (PHF) which - that is the hypothesis - is equivalent to the sensation of local thermal discomfort. The sensation of draught is strongly dependant of the fluctuation frequency. In fig. 2, from (9) the degree of discomfort, dependant of this frequency, can be seen.

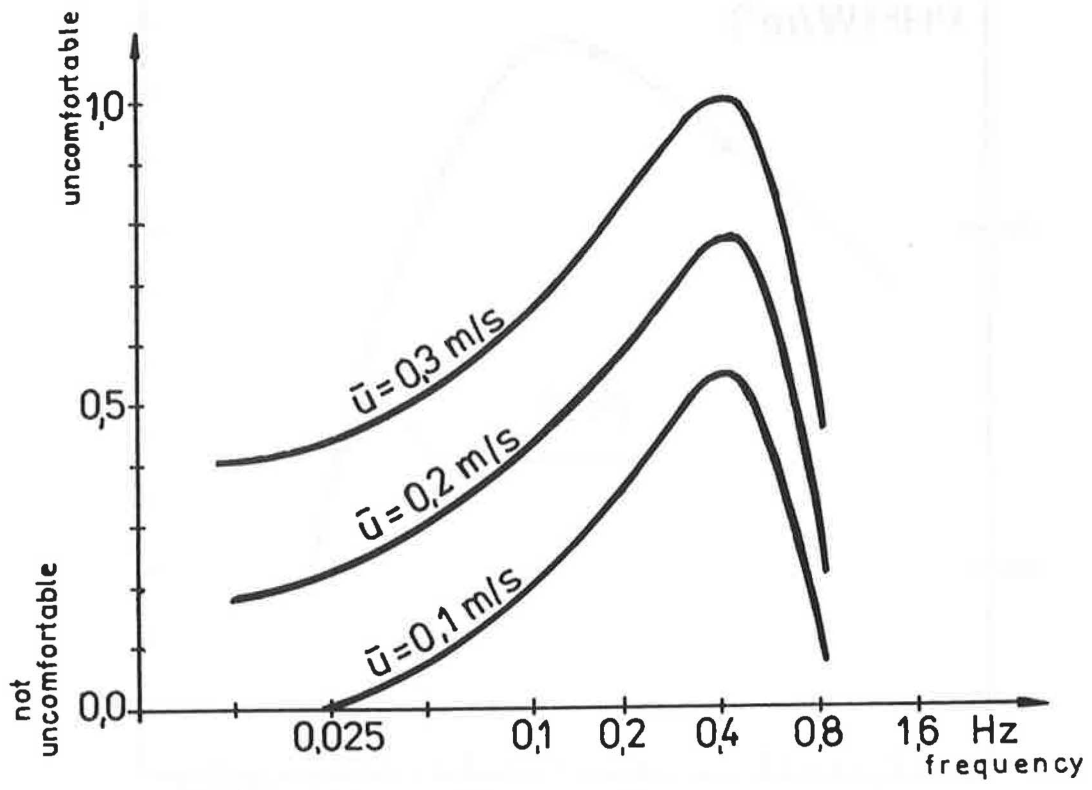

Fig. 2. Correlation between the frequency of air velocity variations and the degree of local discomfort. (from 9)

In fig. 3 a schematic diagram of the instrument is shown, and in fig. 4 the correlation between the fluctuation frequency and the perceived heat flux is given. The shape of the curve is in good agreement with fig. 2 which shows the correlation between the frequency and the discomfort.

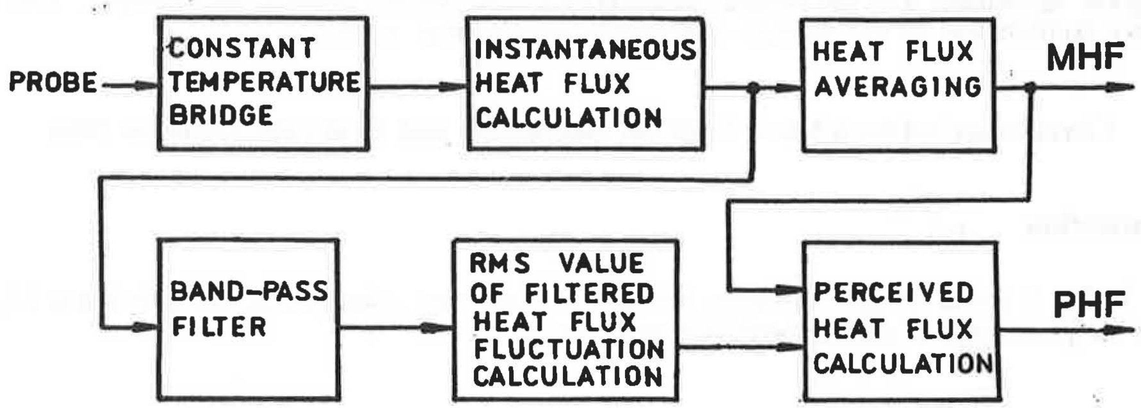

Fig. 3. Diagram of instrument for calculation of perceived heat flux.

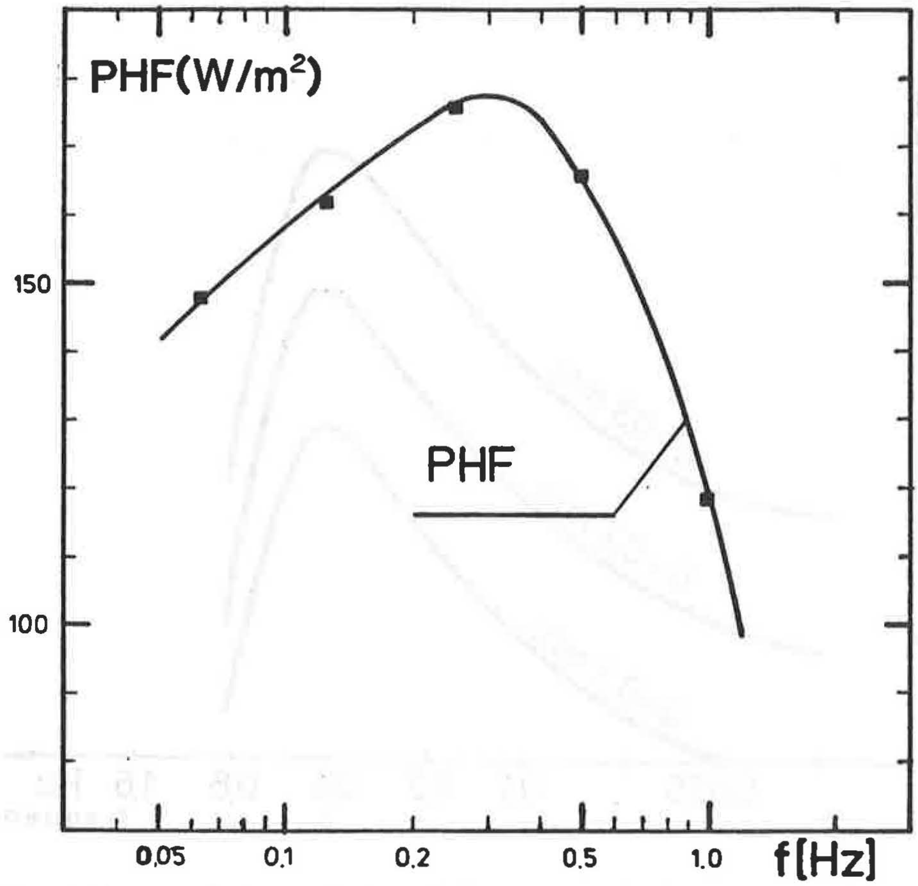

Fig. 4. Correlation between the frequency of air velocity variations and the measured perceived heat flux (PHF).

The skin element is double sided for two reasons. It is a simple way to avoid heat loss from the back of the heated ceramic elements. The difference in the mean heat flux from the two opposite elements can directly be transformed to a thermal asymmetry. In an environment with air movement it is not exactly the plane radiant temperature asymmetry defined in (1). The measuring result may be influenced by different convective heat losses from the two elements. On the other hand the asymmetry measured by this skin element is in good agreement with the human sensation in an asymmetric thermal environment. This is also a combination of the radiant - and the convective heat transfer.

Correlation between Local Thermal Discomfort and Heat Loss from the Skin

Convection

In fig. 5 (from 4) the correlation between the mean air velocity ($\overline{v}$), the turbulence (T_u) and the percentage of dissatisfied (PD) are shown.

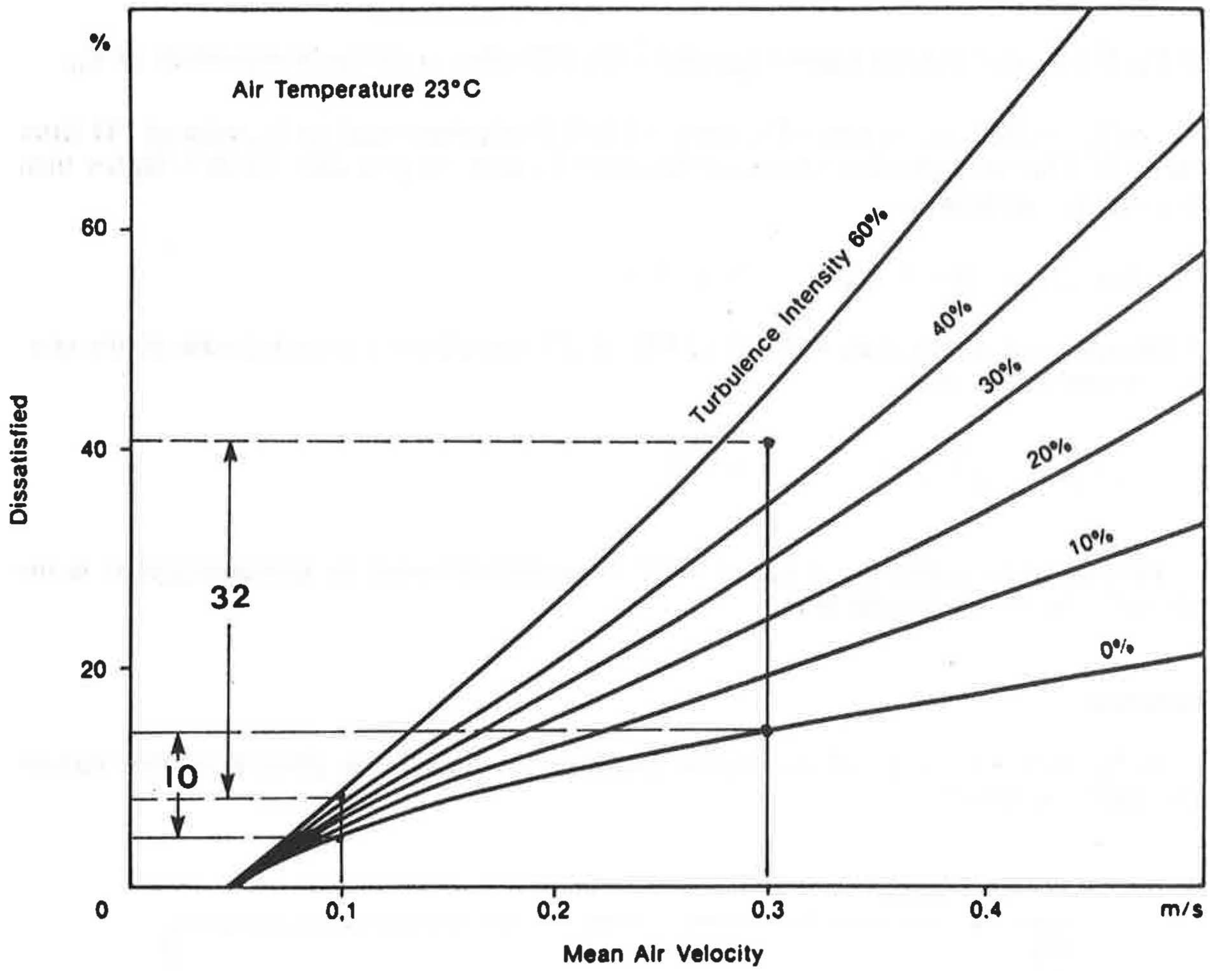

Fig. 5. Percent dissatisfied as a function of mean air velocity and turbulence intensity calculated from the model of draught risk. The diagram applies for an air temperatur of 23°C. (from 4).

For a laminar air flow, an increase of $\overline{v}$ from 0.1 to 0.3 m/s may cause an increase of PD from 4 to 14%. The corresponding increase of heat loss is, according to (7) for the actual air temperature, (t_{air} = 23°C)

$$\Phi_{conv} = 12 \cdot \sqrt{V}(t_{skin} - t_{air}) \quad W/m^2$$

$$\Delta\Phi_{conv} = 12(\sqrt{0.3} - \sqrt{0.1})(34 - 23) = 30 \quad W/m^2$$

consequently an increase of PD of 1% is caused by an increase of the convective heat loss equal to:

$$\frac{\Delta\Phi_{conv}}{\Delta PD} = \frac{30}{14-4} = 3.0 \quad W/m^2$$

Influence of Turbulence

In fig. 5 it is seen that for a given t_{air} and $\overline{v}$ the PD-value is strangely dependant of T_u.

For T_u = 50% an increase of $\overline{v}$ from 0.1 to 0.3 m/s may cause an increase of PD from 9 to 41%. The corresponding convective heat loss is, according to (10), 10-20% higher than for a laminar air flow: ~

$$\Delta\Phi_{conv} = 30 \cdot 1.15 \sim 35 \ W/m^2$$

In this turbulent situation an increase of PD by 1% corresponds to an increase of the convective heat loss of only:

$$\frac{\Delta\Phi_{conv}}{\Delta PD} = \frac{35}{41-9} \sim 1.1 \ W/m^2$$

This increased sensitivity is caused by an interaction between the thermoreceptors in the exposed skin and the human brain.

Radiation

In fig. 6 the percentage of dissatisfied caused by a cold surface, given as a plane radiant asymmetry, is shown.

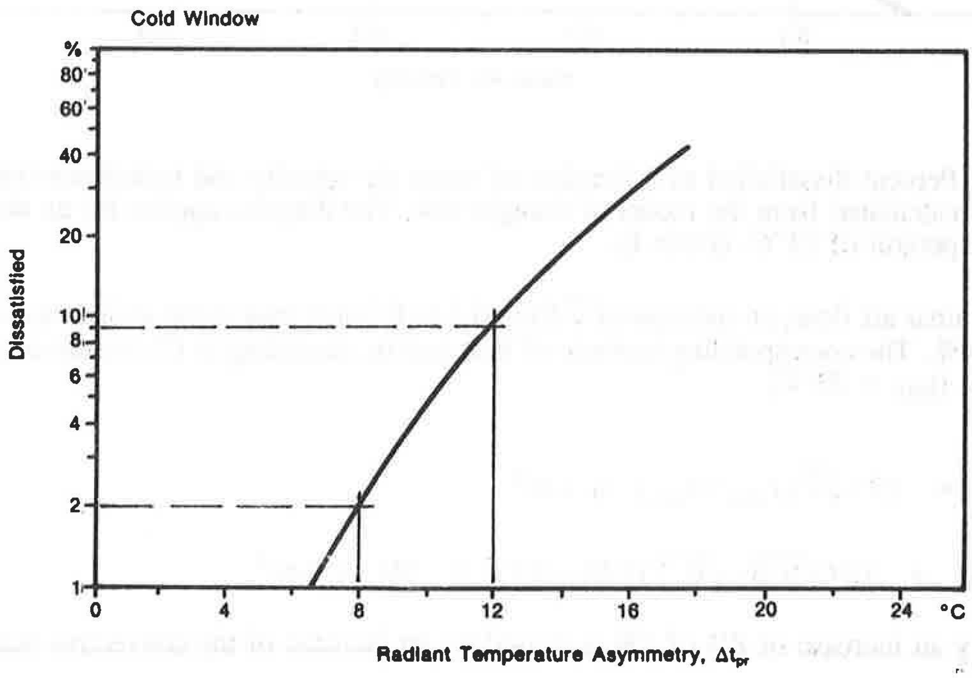

Fig. 6. Percentage of dissatisfied (PD) a function of the radiant temperature asymmetry (Δt_{pr}).

Assuming a room temperature of 23°C, a decrease of the cold surface temperature from 15 to 11°C - corresponding to an increase of Δt_{pr} from 8 to 12 K - may, according to fig. 6, increase the PD-value from 2 to 9%. The corresponding increase of the radiant heat loss is:

$$\Delta\Phi_R = 0.95 \cdot 5.77 \cdot 10^{-8}((273+15)^4-(273+11)^4) = 20.5 \quad W/m^2$$

an increase of the radiant heat loss equal to 1% increase of the PD-value is:

$$\frac{\Delta\Phi_R}{\Delta PD} = \frac{20.5}{9-2} = 2.9 \quad W/m^2$$

or almost a similar correlation as earlier found for laminar convection.

Comparison between the Skin Element and a new Draught Risk Equation

Investigations on human response to draught have recently been created by turbulent air flows typical for ventilated spaces (3) and (4).

A result of these investigations is a new draught equation, which predicts the percentage of dissatisfied people due to draught as a function of air temperature, mean air velocity and turbulence intensity:

$$PD = (3.14+0.37 \cdot \bar{v} \cdot Tu)(34-t_a)(\bar{v}-0.05)^{0.62} \qquad \text{(I)}$$

PD is the percentage of dissatisfied
$\bar{v}$ is the mean air velocity, m/s
Tu is the turbulence intensity, %
t_a is the air temperature, °C

The equatation is valid for: $20°C < t_a < 26\ °C$
$0.05 < \bar{v} < 0.4$ m/s
$0 < Tu < 70\%$.

A comparison has been made between this new equation and the instrument described here.

Measurement

The investigation is carried out in a constant temperature chamber, in which a wind tunnel can create different air velocities, degrees of turbulence and air temperatures.

The investigation includes measurements of the artificial skin element properties for different air velocities and turbulence intensities. The influence of different air velocities and different degrees of turbulence has been researched. Low turbulence air flow (Tu = 7%), medium turbulence (Tu = 25%) and high turbulence (Tu = 55%), have been created in the chamber. These degrees of turbulence have been maintained with an accuracy of ±5%.

The air temperature, plane radiant temperature, air velocity and standard deviation have been measured by an Indoor Climate Analyzer Type 1213. The percentage of dissatisfied has been calculated according to equation I. The special interface in 1213 and a personal computer have been used for the calculation.

The new instrument has been used for measurements of the Perceived Heat Flux (PHF) simultaneously with the measurement of each of the above parameters. The distance between the different transducers during measurements has been less than 0.4 m, fig. 7.

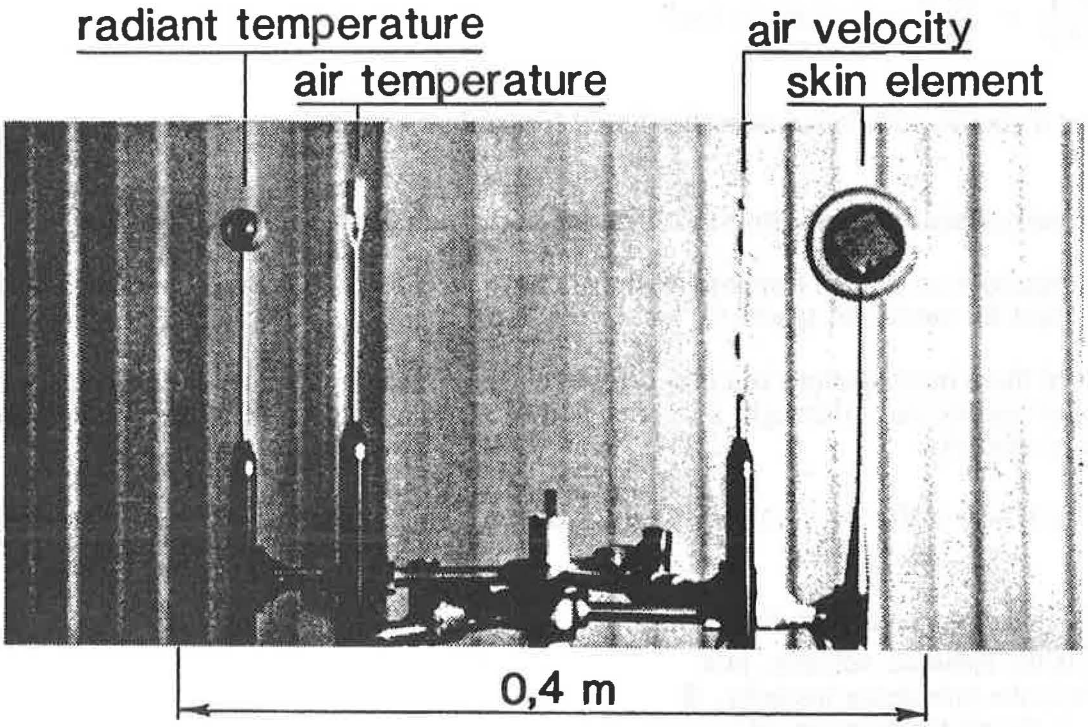

Fig. 7. Transducers. Type and relative position during measurements.

The correlation between PHF and the air velocity for three degrees of turbulence at a constant air temperature is shown in fig. 8, and the correlation given between PHF and the air velocity for three different temperatures at a constant degree of turbulence is shown in fig. 9.

Approximation of Measuring Results

Three different approximations have been tested:

1. a straight line $y = a + bx$
2. a power curve $y = a \cdot b^x$
3. An exponential curve $y = a \cdot e^{bx}$

The determination coefficient (R^2) for the three tests is given in table 1. The straight line gives the best approximation if all three temperatures are taken into account. The regression coefficients for the best fitting straight lines are given in table 1. The curve fitting for all measuring points is given in fig. 10.

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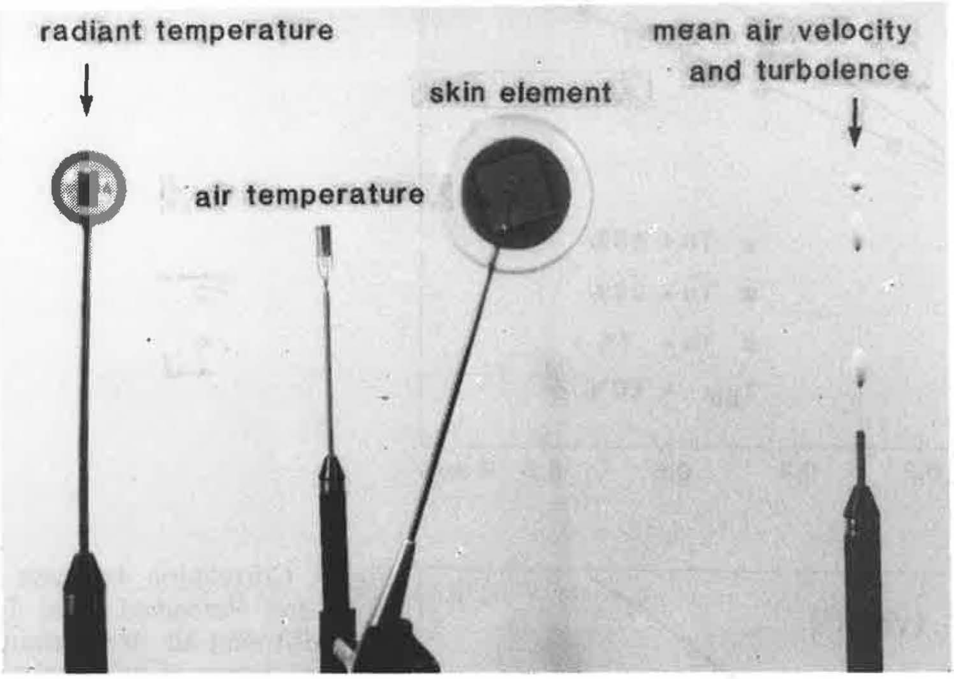

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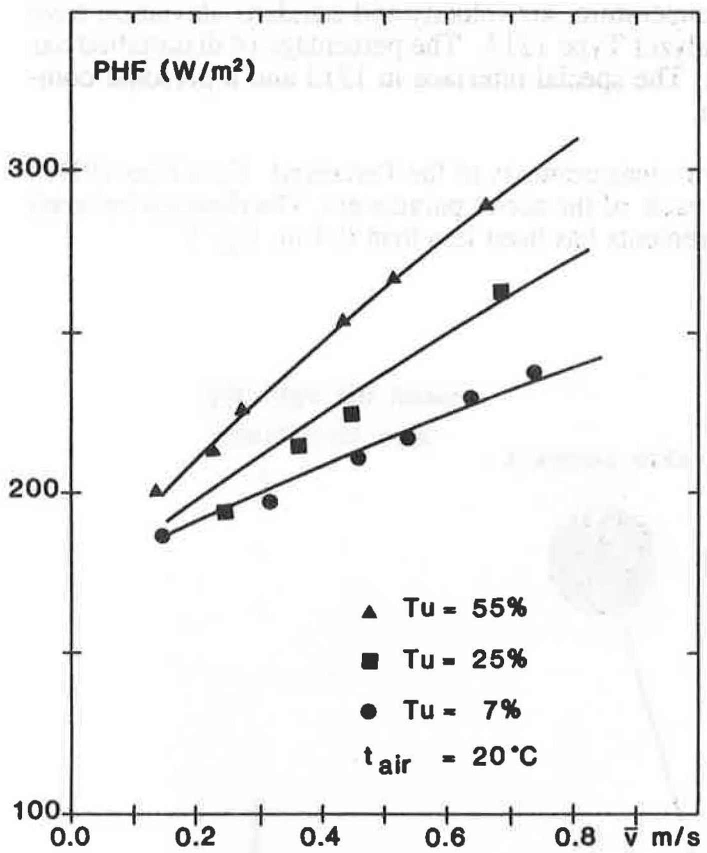

Fig. 8. Correlation between mean air velocity and Perceived Heat Flux for three different degrees of turbulence at a constant air temperature.

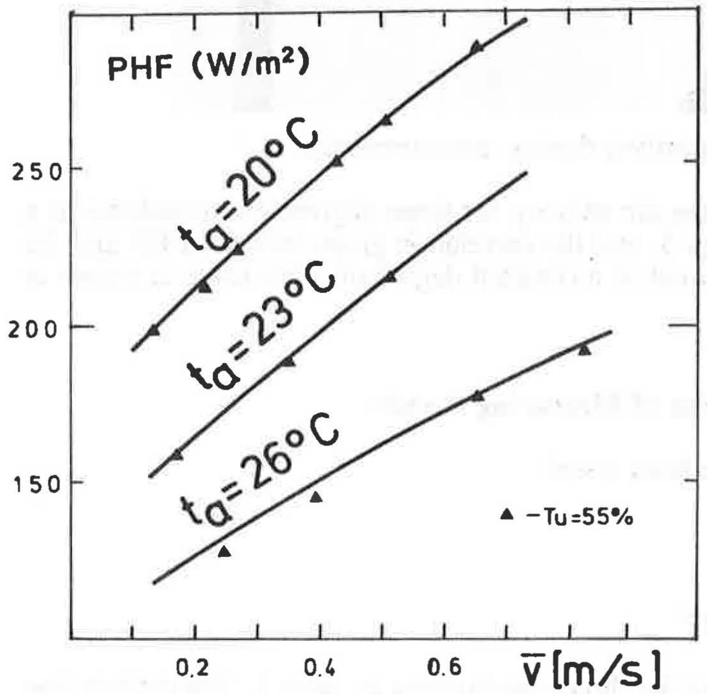

Fig. 9. Correlation between air velocity and Perceived Heat Flux for three different air temperatures at a constant degree of turbulence.

Equation	coefficient	air temperature		
		20	23	26
$y = a + b \cdot x$	R^2	0.940	0.946	0.942
$y = a \cdot b^b$	R^2	0.877	0.982	0.925
$y = a \cdot e^{bx}$	R^2	0.864	0.963	0.899
$y = a + b \cdot x$	a	-156	-133	-128
	b	0.919	0.980	1.120

Table 1. Determinations and regression coefficients for different approximation tests of measuring results.

Discussion

In (12) it is concluded that discomfort caused by radiation and air velocity are independent and additive. This means that the resultant heat loss from the skin element can be used as a parameter for calculation of PD. It is found that an 3 W/m^2 increase of the heat loss - convective or radiant - may increase PD by 1%. But if there is turbulent air movements the influence on PD of the increase of the heat loss is up to three times higher.

A fairly good correlation is found between the PHF-value measured by the instrument and the PD-value calculated from the new equation. The result of the comparison is shown in table 1 and fig. 10. It will, however, be seen that it is necessary to measure not only the PHF but also the air temperature before the PD-value can be found. This is surprising because the heat loss from the skin element, as well as the PD-value according to equation I, is proportional to the difference between 34°C and the actual air temperature.

The reason is that the sensitivity to draught is strongly dependant of the clo-value, and in the draught test all persons have adjusted their clothing to obtain general thermal comfort at the actual air temperature (20, 23 or 26 °C) and a mean air velocity around 0.2 m/s.

Because of the higher clo-value, the sensitivity to draught has been lower at 20°C than at 23 and 26°C. This effect is included in the draught equation.

There are two possibilities for determining PD from measurement of PHF. The air temperature can be measured simultaneously with the PHF and then the PD-value can be calculated from the following equation:

$$PD = (t_{air} - 37) \cdot 10 + PHF \quad (\%) \qquad \text{II}$$

It is seen that the correlation between PD and PHF is identical to that previously found for turbulent air flow (1% ~ 1 W/m^2).

Equation II is shown graphically on fig. 10, dotted lines.

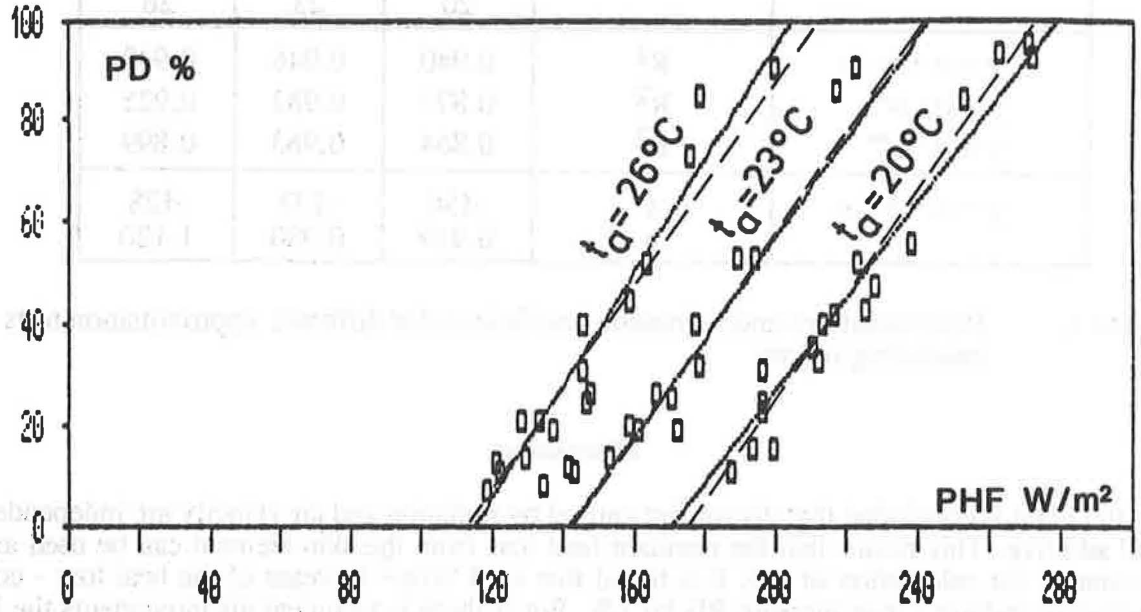

Fig. 10. Measured values and the linear regression lines for three air temperatures. The dotted lines are a graphic explanation of equation II.

Another - and maybe better - solution could be an incorporation of the actual clo-value in the calculation of the PD-value.

According to ISO7730 (1) the optimum clo-value for 1.2 met and 20°C is 1.25 clo. At 26°C, the optimum clo-value is 0.25 clo, consequently a good approximation to fig. 10 can be obtained if the following equation III is incorporated in the microprocessor of the instrument.

$$PD = -(1.6 + I_{clo}) \cdot 60 + PHF \quad \% \qquad \text{III}$$

This means, that if there is a possibility for a setting of the actual clo-value on the instrument, the expected degree of dissatisfied (PD) can be read directly on the display.

Conclusion

For a given air temperature a good correlation is found between the perceived heat flux measured with the new instrument, and the expected percentage of dissatisfied due to draught calculated by a new draught risk equation.

The sensation of draught is dependant of the actual clo-value. Assuming a clo-value in agreement with ISO7730 the degree of local discomfort can be measured directly after a setting of the actual clo-value on the instrument.

The instrument includes both the convective and the radiant heat loss. It is expected that the measuring result includes discomfort caused by air velocity and turbulence but also by an increased radiant heat loss to cold surfaces. This expectation has to be tested in controlled environments where test persons and a skin element are exposed to a similar combination of draught and radiation.

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