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Publication date:
1977

Document Version
Publisher's PDF, also known as Version of record

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Citation (APA):
Madsen, T. L. (1977). *Thermal comfort measurements*. Technical University of Denmark, Department of Civil Engineering.

No. 2383

THERMAL INSULATION LABORATORY
Technical University of Denmark

REPORT NO. 50

THERMAL COMFORT MEASUREMENTS

PROF. TH. LUND MADSEN

For many years it has been desirable to be able to determine directly man's predicted thermal sensation in a given environment. This determination has been difficult because in order to sustain thermal comfort a balance must be achieved between no less than six parameters:

Air temperature	(t_a)
Air velocity	(v)
Mean radiant temperature	(MRT)
Vapor pressure in air	(p_a)

for the environment and

Activity level	(M)
Clothing	(I)

for people.

The ideal solution would be to determine the expected degree of thermal sensation with a single instrument. To enable us to do this, it is necessary to have a well defined unit to represent the degree of thermal sensation.

Such a unit appeared in 1970 when Fanger defined the PMV (predicted mean vote) index[1]. This index gives the expected degree of thermal comfort in relation to all the above mentioned six thermal parameters.

The PMV-index is based on Fanger's comfort equation from 1967[2] and the usual psycho-physical ASHRAE scale. Only this has been changed to form a symmetrical scale around zero.

The PMV scale is therefore:

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

The comfort equation describes the conditions under which a large group of people will on average vote for zero on the above scale. The problem was to combine the comfort equation with the different degrees of thermal discomfort as given on the PMV scale.

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It is well known that the organism is capable of maintaining a heat balance even when the ambient temperature varies within wide limits. Within a relatively narrow zone including the comfort zone, the heat balance is maintained by vasomotor action, and under greater thermal loads, by sweating or shivering.

It is reasonable to presume, therefore, that the degree of thermal discomfort is closely related to the thermal load which the environment impresses on the person, and consequently the degree of thermal discomfort can be expected to be a function of the thermal load.

Fanger has defined the degree of thermal discomfort (the PMV value) at a given activity level as a function of the difference between the internal heat production (metabolism) and the heat loss to the actual environment from a person with skin temperature and sweat production corresponding to thermal comfort at the actual activity level.

It is now possible to calculate the PMV value for all combinations of the above-mentioned six thermal climate factors. However, the expression for the calculation of the PMV value is so complicated that it is suitable only for computer calculation. Fanger[1] has calculated and given in tabular form the PMV value for six activity levels, seven clo values, nine air velocities, one relative humidity and eight temperatures. The air temperature and the mean radiant temperature are assumed to be the same. Correction diagrams are given so that the PMV value can be determined for other humidities, and where the mean radiant temperature is not equal to the air temperature.

INSTRUMENTATION

Over the years many instruments have been developed to measure one or more of the parameters with the purpose of calculating the expected degree of thermal comfort.

The first instrument was Frankenhauser's homeotherm developed in 1910. Later developments included Dufton's eupatheoscope in 1932[3], and Winslow's thermal integrator in 1935[4]. Many more are named in the literature; among the latest is the R meter, developed at the Pierce Foundation Laboratory in New Haven at the end of the 1960's[5]. With the R meter it is possible to determine air temperature, air velocity, mean radiant temperature plus the operative temperature and the effective radiant field.

No matter which of the above-mentioned instruments is used, it is still necessary, after measuring, to make certain additional calculations and estimates before arriving at the expected thermal sensation. Moreover, only a limited number of these instruments is available in scientific laboratories, and they are therefore not readily available for the practising engineer.

The Comfy-Test EQ 21[6,7]

Recently, at the Thermal Insulation Laboratory of the Technical University of Denmark, an instrument has been developed which, by direct measurement of the predicted mean vote (the PMV value), gives direct information on the occupant's expected thermal sensation. The comfort meter, available commercially, is in principle formed by the items shown in Fig. 1, and in the final form it is shown in Fig. 4. As accurately as possible, a sensor measures the dry heat loss from a person in thermal comfort in the given surroundings and wearing the clothing as adjusted on the instrument. In other words, it is a sensor which measures t_a, MRT, and v's combined thermal effect on this person. A control instrument governs the supply of heat to the sensor, so that its surface temperature remains constantly equal to the average outer surface temperature of the person in thermal comfort wearing the clothing as set on the instrument. A new setting of clothing will therefore produce a partial change in calculation value for the determination of PMV value and a partial change in the surface temperature so that it corresponds to the new clo value.

The instrument also contains an analog resistance network (Fig. 2) which calculates the total heat loss from a person in thermal comfort in the actual environment, based upon the measured dry heat loss and the set vapor pressure. By comparing, in the network, the desired heat loss with the actual activity level as set on the instrument, an electrical measuring value, a voltage difference, is obtained which shows directly on a meter the desired PMV value.

The Sensor

The most technically interesting part of the new comfort measuring device is the sensor itself. The aim in developing the sensor was to achieve an optimal simulation of a person from a thermal point of view. This is achieved by appropriately selecting the sensor's:

size
shape
orientation
radiation properties
surface temperature

Size. The size is chosen so that the relationship between the heat emittance by convection and by radiation is the same as for a person. According to Fanger[1], the effective radiant area of a person is only 0.7 times as great as the convection area. This is due to the fact that a reciprocal radiation exchange occurs between some parts of the body, e.g. between the inner sides of the legs and between the arms and the sides of the body. On the other hand, the sensor's radiation- and convection-areas are equal. By now making the sensor so small that its convective heat transfer coefficient is 1/0.7 = 1.4 times as great as man's, the correct relation between the sensor's convective and radiant heat loss is obtained. The fact that the sensor's combined heat transfer coefficient is 1.4 times greater than a person's heat transfer coefficient in the same thermal environment is corrected within the calculating unit.

Shape And Orientation. The shape and orientation of the sensor are selected with the aim of achieving the correct radiation exchange between the sensor and its surroundings. Table 1 shows the radiation area factor in different directions for both sensor and man. There is a fairly good agreement between man and sensor for both standing and sitting positions, corresponding to the sensor being placed vertically and at an angle (30 deg) to the vertical respectively. The orientation of the sensor can be chosen by setting the cylindrical connecting link between sensor and tripod.

Radiation Properties. The radiation properties are chosen so that for long-wave radiation it corresponds to the absorptance for both a nude and a clothed person. For short-wave radiation (solar) the absorptance depends on the color of the surface. One cannot simulate persons in both light and dark clothing with a single sensor. The color of the sensor is chosen so that it corresponds to uncovered skin and rather light clothing.

Surface Temperature. By means of the measuring instrument's adjustment knob for clothing shown in Fig. 3, the regulating system for controlling the surface temperature of the sensor can be varied, so that after a short period of adjustment (approx 2 min) it assumes the same value as the mean outer surface temperature of a person in thermal comfort, with clothing corresponding to that set on the instrument. In this case the effect conveyed to the sensor (W/m^2) becomes a direct measure for the person's dry heat loss to the environment.

COMPARISON OF MEASUREMENTS

A series of simultaneous measurements have been made under different conditions often encountered in practice, with the aim of comparing the PMV value measured directly using the comfort meter, with the PMV value calculated on the basis of the individual environmental parameters. It was also desired to examine the influence that the variation of MRT and v have upon the comfort meters determination of PMV value.

Facilities And Instrumentation

The measurements were taken in two different environmental situations:

A. A Heavy Room Insulated From The Surroundings And Situated Underground. The room ($h \times l \times b = 2.5 \times 7.2 \times 6.0$ m) can be heated electrically, but the most uniform thermal field is obtained when the room stands for several days without heat addition (i.e. t_a = MRT) and without ventilation (i.e. $v < 0.05$ m/s). In this room the individual environmental parameters can be determined with great accuracy (±0.1 deg C. It is therefore possible from the measurements in this room to determine the measuring accuracy of the comfort meter.

B. A North-Facing Laboratory Room ($h \times l \times b = 2.4 \times 12 \times 5.4$ m). The room had windows and also mechanical ventilation, and in order to change the MRT, a vertical black panel radiator ($h \times l = 0.5 \times 1.75$ m) was positioned on one wall. The surface temperature of the radiator was controlled by a thermostatic reservoir with possibilities for both cooling and heating. The usual technical measuring problems can be expected in this room in connection with determination of the individual environmental parameters.

The following measuring equipment was used for determining the individual environmental parameters:

t_a was measured with a copper-constantan thermoelement, 28 gages. A length of 200 mm nearest the soldering point was wound into a spiral and surrounded with a polished metal cylinder.

MRT was measured with a similar thermoelement centrally placed in a 4" black globe of polyetylen.

Air velocity (v) was measured with a DISA hot wire anemometer k55 system with a measuring band 0.05-10 m/s.

t_a and MRT were measured and registered on a digital datalog Digitec 1590 TC which gave directly the temperature in deg C to 1 decimal place. During calibration with the actual thermoelements the accuracy was found to be better than ±0.2 deg C.

MRT can be calculated from the formula:

$$T_w^4 = T_g^4 + 0.103 \cdot 10^4 \cdot \sqrt{v}(tg - ta) \qquad \text{(page 203 in Ref 8)}$$

With conversion to deg Centigrade, m/s and to a 4 in. globe the expression becomes:

$$\underline{(MRT + 273)^4 = (tg + 273)^4 + 0.272 \cdot 10^9 \cdot \sqrt{v}(tg - ta)}$$

A computer was used to calculate the PMV values based on Fanger's formula using the individually measured environmental parameters. The PMV values can also be determined by interpolation in the tables of Ref 1.

RESULTS

The results of the above-mentioned measurements are tabulated in Tables 2-6. The PMV value is measured and calculated for 5 activity levels, 2 clo values and 2 air velocities.

The results in Table 2 are derived from well defined environmental parameters (t_a = MRT and $v < 0.05$ m/s).

In Table 3, the sensors reaction to a point radiation source was investigated. A 250 watt infrared lamp was placed 1.6 m from the globe, and sensor and reading were taken with (A) the radiation direction perpendicular to the sensor's axis, and with (B) the radiation direction parallel with the sensor's axis. There was a significant difference in PMV value in the two instances, a difference that a person would feel but which is not disclosed by the globe.

A similar comparison was made in Table 4, where the PMV values were measured with an air flow perpendicular to the sensor's axis and parallel to the sensor's axis. The air flow was generated by an axial-flow fan with variable speed, placed approx 2.5 m from the sensor. The fan speed was adjusted to give an air velocity at the sensor of 1.0 m/s. It can be seen from Table 4 that the PMV value is almost unaffected by the direction of the air flow. This is in agreement with Ref 9 which showed that the preferred ambient temperature, even when at an air velocity of 0.8 m/s, was almost unaffected by the direction from which the air flow came. This must be due to the convective heat loss being independent of the air flow direction.

Tables 5 and 6 show the results from room B. The globe and the sensor were placed symmetrically and at the same distance (0.6 m) from the radiator. The effect of varying radiator temperature can be seen in Table 5.

The air velocity around the sensor can be varied by using the above-mentioned fan. The air velocity was adjusted before each measurement using a hot wire anemometer and the results are tabulated in Table 6.

APPRAISAL OF RESULTS

The standard deviation (s) for the two measuring methods is shown in Table 7. The results are divided into 3 groups:

I The difference between the measured and the calculated PMV values in Table 2 is presumably due to the comfort instrument. Its measuring accuracy under these conditions is ±0.05 PMV.

II There is a large difference between sensor and globe value when measuring with radiation parallel to the sensor's axis. This is due to the fact that the globe takes no account of a person's projected area factor, which varies from 0.08 to 0.35 depending on the direction of radiation. The sensor, however, is developed to simulate a human being and therefore includes this variation.

III At the remaining measurements, the deviation between the two methods of measuring has been calculated to ±0.12 PMV. Comparing with I, one must assume that the measuring inaccuracy in practical instances will be greater when using traditional equipment than when using the new instrument.

It can be generally stated that all these measurements were made with well-calibrated instruments and under constant thermal conditions. It is reasonable to suppose that actual measurements in practice will include a greater error for both measuring methods. Non-steady-state conditions, however, will have much less effect on the Comfy-Test's measurements because this instrument always integrates the corresponding values of t_a, MRT and v, whereas traditional equipment cannot measure all parameters at the same position simultaneously.

The following will show that in practice it is the occupants and not the measuring equipment that sets the limits for how accurately the predicted degree of thermal comfort can be decided.

Measuring Accuracy

The mathematical expression for calculating the PMV value is an excellent tool for closely analyzing the needed accuracy one should use to measure the predicted degree of thermal comfort, including an estimation of the justification in neglecting an actual measurement of water vapor pressure. This omission is perhaps the only apparently illogical part of the instrument's construction.

The PMV value can be expressed as:

$$PMV = f(t_a, v, MRT, p_a, M, I)$$

where M and I cannot be measured but must be estimated considering the knowledge we have of the application of the actual space.

Neither M nor I can be given with great accuracy. M varies for the same activity from person to person depending on the physiological and ergonometric conditions, and I is, among other things, dependent on the fit of the clothing.

Considering these conditions the adjustable values on the instrument have been selected as follows:

For activity level (M): 40, 50, 60, 70, 80, 90, 100,
120, 140, 160, 180 and 200 (W/m^2)

and for clothing (I): 0.0, 0.1, 0.2, 0.3, 0.4, 0.5,
0.6, 0.8, 1.0, 1.2, 1.5 and 2.0 (clo)

Now the unavoidable uncertainty in the PMV value arising from M and I can be determined according to the classic measuring theory:

$$u_{PMV_{M,I}} = \sqrt{\left(\frac{PMV}{M} u_M\right)^2 + \left(\frac{PMV}{I} u_I\right)^2}$$

In Table 8, $u_{M,I}$ is calculated for several typical adjustments. As can be seen from the table, the value is practically independent of the selected combinations. The value can (with good approximation) be set at ±0.25 PMV.

The degree of combined uncertainty of the PMV value will now depend on the following two factors:

a. The Instruments Error (u_{PMV_C}). Measurements in Tables 2-6 suggest that the comfort meter's error is, in practice, less than ±0.10 PMV. If we calculate with $u_{PMV_C} = \pm 0.10$ PMV we obtain:

$$u_{PMV_{M,I}} + u_{PMV_C} = \sqrt{0.25^2 + 0.10^2} = \pm 0.27 \text{ PMV}$$

b. Knowledge Of p_a. p_a can be adjusted with an accuracy of ± 1 mbar, if it is measured accurately enough. According to Table 7, this gives:

$u_{PMV_{p_a}} = \pm 0.03$ PMV and thereby a combined uncertainty of:

$$u_{PMV} = \sqrt{0.25^2 + 0.10^2 + 0.03^2} = \pm 0.27 \text{ PMV}$$

Even if p_a is not known very accurately but is decided from a rough knowledge of t_a and RH, giving for example:

$$u_{t_a} = \pm 2 \text{ deg C and } u_{RH} = \pm 10 \text{ percent}$$

we obtain $u_{p_a} = \pm 4$ mbar and $u_{p_a} = \pm 0.12$ PMV and thereby:

$$u_{PMV} = \sqrt{0.25^2 + 0.10^2 + 0.12^2} = \pm 0.29 \text{ PMV}$$

i.e., a moderate increase (7 percent) of the combined uncertainty. This confirms that accurate knowledge of humidity is not necessary. This applies however only to those comfort measurements at lower activity levels.

DISCUSSION

In practice, the quite unprecise knowledge of activity level and clothing set a minimum limit for how accurately the PMV value can be determined for a given situation. At the same time, the dependence of the PMV value on namely these two parameters indicated the importance of always being aware of them when considering a thermal environment. This is always the case when using the instrument described, which especially concentrates attention toward these two parameters. The combination of M and I which will give optimal thermal comfort in the given environment can therefore be directly read from the instrument. This has a great psychological effect when persuading occupants that even the best indoor environmental systems may need a change in the personal parameters, especially clothing, if the thermal comfort is to be sustained under the same environmental conditions which satisfy the other occupants.

The influence of vapor pressure on the PMV value is so minimal that an accurate measurement is unnecessary. An error of ± 4 mbar will give no significant increase in error of the PMV value. For example, if p_a is selected as 12 mbar then the degree of error at $t_L = 24$ deg C will not be exceeded as long as the relative humidity lies between 27 and 54 percent. This explains the reason for omitting a humidity transducer in the instrument and setting p_a directly. This also gives the possibility of showing the occupants how little effect p_a has on the degree of thermal comfort.

CONCLUSION

1. The new comfort meter provides a quick, direct measurement of the predicted mean vote in a given space.
2. Comparison with calculated PMV values based on separate measurements of the thermal parameters in typical environments shows good agreement.
3. In cases where man is exposed to asymmetric radiation the comfort meter gives a better approximation to the PMV value than can be calculated from traditional measurements of the thermal parameters.
4. Inaccuracy of a certain PMV value is due mainly to the fact that in practice it is difficult to state activity level and clothing with great accuracy. In order to compare different thermal environments, to measure the thermal effect produced by changes in the heating and ventilating system, as well as for the repreducibility of thermal environmental measurements in common, it is still important that the thermal parameters are measured accurately.
5. The comfort meter measures the thermal effect of t_a, MRT, and v, simultaneously and at the same position; this gives a good reproduction especially under non-steady-state conditions.

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TABLE 1

Comparison Between the Projected Area Factor for Man and Sensor in Standing and Seated Positions

orientation		man			sensor		
man	sensor	up-down	left-right	front-bag	up-down	left-right	front-bag
standing	I	0.08	0.23	0.35	0.08	0.28	0.28
seated	II	0.18	0.22	0.30	0.18	0.28	0.22

TABLE 2

Calculated and Measured PMV Values, at Well-Known Environmental Parameters - Room A

p_a	I	M	t_a	MRT	v	PMV		difference
mbar	clo	W/m^2	°C	°C	m/s	calculation from parameters	measured by comfort meter	cal.-mes.
10 ~ 55% RH	0.5	80	16.2	16.2	<0.05	-1.90	-1.98	+0.08
		100				-1.10	-1.10	0.0
		140				-0.18	-0.15	-0.03
		180				+0.58	+0.55	+0.03
	1.0	60	16.2	16.2	<0.05	-1.74	-1.76	+0.02
		80				-0.70	-0.72	+0.02
		100				-0.14	-0.05	-0.09
		140				+0.58	+0.62	-0.04
		180				+1.08	+1.13	-0.05
2 ~ 11% RH		60	16.2	16.2	<0.05	-2.01	-2.00	-0.01
		80				-0.86	-0.89	+0.03
		100				-0.26	-0.18	-0.08
		140				+0.52	+0.51	+0.01
		180				+1.03	+1.02	+0.01

TABLE 3

Calculated and Measured PMV Value
A: With a Radiation Field at a Right Angle to the Axis
B: With the Same Radiation Field Along the Sensor

	p_a	I	M	t_a	MRT	v	PMV		difference cal.- mes.
	mbar	clo	W/m^2	°C	°C	m/s	calculation from parameters	measured by comfort meter	
A	10	0.5	80	16.1	20.4	<0.05	-1.42	-1.60	-0.18
			100				-0.70	-0.70	0.0
			140				+0.20	+0.16	+0.04
			180				+0.92	+0.81	+0.11
		1.0	80	16.1	20.6	<0.05	-0.27	-0.33	+0.06
			100				+0.16	+0.25	-0.09
			140				+0.84	+0.88	-0.04
			180				+1.46	+1.36	+0.10
B	10	0.5	80	16.1	20.8	<0.05	-1.38	-1.91	+0.53
			100				-0.65	-0.99	+0.34
			140				+0.23	-0.05	+0.28
			180				+0.95	+0.61	+0.34
		1.0	80	16.1	20.8	<0.05	-0.25	-0.58	+0.33
			100				+0.18	+0.08	+0.10
			140				+0.85	+0.73	+0.12
			180				+1.48	+1.22	+0.22

TABLE 4

Calculated and Measured PMV Values
A: With an Airflow at a Right Angle to the Sensor's Axis
B: With the Same Airflow Along the Axis

	p_a	I	M	t_a	MRT	v	PMV		difference cal.- mes.
	mbar	clo	W/m^2	°C	°C	m/s	calculation from parameters	measured by comfort meter	
A	10	0.5	100	16.1	16.1	1.0	-2.38	-2.22	-0.16
			140				-1.16	-1.11	-0.05
			180				-0.30	-0.29	-0.01
B	10	0.5	100	16.1	16.1	1.0	-2.38	-2.33	-0.05
			140				-1.16	-1,18	+0.02
			180				-0.30	-0.35	+0.05

TABLE 5

Calculated and Measured PMV Values, at the Three Different Mean Radiant Temperature Levels

p_a	I	M	t_a	MRT	v	PMV		difference calc.- meas.
mbar	clo	W/m^2	°C	°C	m/s	calculation from parameters	measured by comfort meter	
14	0.5	60	22.0	17.9	0.10	-2.07	-2.08	+0.01
			22.1	22.6	0.08	-1.20	-1.27	+0.07
			24.0	28.7	0.10	+0.24	+0.15	+0.09
	1.0		22.0	18.0	0.10	-0.70	-0.68	-0.02
			22.2	22.4	0.08	-0.14	-0.06	-0.08
			24.1	28.9	0.10	+0.94	+0.98	0.0
	0.5	80	22.0	17.9	0.10	-0.90	-0.88	-0.02
			22.1	22.6	0.08	-0.22	-0.28	+0.06
			24.0	28.7	0.10	+0.76	+0.80	-0.04
	1.0		22.0	18.0	0.10	+0.04	+0.11	-0.07
			22.2	22.4	0.08	+0.46	+0.60	-0.14
			24.1	28.9	0.10	+1.22	+1.40	-0.18
	0.5	100	22.0	17.9	0.10	-0.25	-0.11	-0.14
			22.1	22.6	0.08	+0.23	+0.26	-0.03
			24.0	28.7	0.10	+1.06	+1.22	-0.16
	1.0		22.0	18.0	0.10	+0.46	+0.62	-0.20
			22.2	22.4	0.08	+0.80	+0.92	-0.12
			24.1	28.9	0.10	+1.44	+1.65	-0.21

TABLE 6

Calculated and Measured PMV Values for Different Air Velocities

p_a mbar	I clo	M W/m^2	t_a °C	MRT °C	v m/s	PMV calculation from parameters	PMV measured by comfort meter	difference calc.- meas.
14	0.5	60	22.1	22.6	0.08	-1.20	-1.27	+0.07
			22.7	22.9	0.20	-1.46	-1.55	+0.09
			22.7	22.7	0.40	-2.00	-2.00	0.0
			23.0	23.0	1.00	-2.57	-	-
		80	22.1	22.6	0.08	-0.22	-0.28	+0.06
			22.7	22.9	0.20	-0.40	-0.55	+0.15
			22.7	22.7	0.40	-0.71	-0.85	+0.14
			23.0	23.0	1.00	-1.10	-1.20	+0.10
		100	22.1	22.6	0.08	+0.24	+0.36	-0.12
			22.7	22.9	0.20	+0.10	+0.08	+0.02
			22.7	22.7	0.40	-0.14	-0.10	-0.04
			23.0	23.0	1.00	-0.42	-0.45	+0.03

TABLE 7

Calculation of Standard Deviation for All Measurements

	Table no.	s^2	s
I	2	$\frac{0.0271}{13}$	0.05
II	3.B.	$\frac{0.7722}{7}$	0.33
III	3A, 4, 5, 6	$\frac{0.4959}{36}$	0.12

TABLE 8

Typical Examples in Deviation of PMV Values as a Result of the Uncertainty in the Given Values of Activity and Clothing

M (W/m^2)	I (clo)	activity			clothing			$u_{PMV_{M,I}}$	vapour pressure		
		$\frac{\partial PMV}{\partial M}$	u_M	$\frac{\partial PMV}{\partial M} u_M$	$\frac{\partial PMV}{\partial I}$	u_I	$\frac{\partial PMV}{\partial I} u_I$		$\frac{\partial PMV}{\partial p_a}$	u_{p_a}	$\frac{\partial PMV}{\partial p_a} u_{p_a}$
60	0.0	0.054	±5	0.27	3.20	0.05	0.16	0.31	0.029	±1	0.03
	0.5	0.044		0.22	2.00	0.05	0.10	0.24			
	1.0	0.041		0.20	1.40	0.10	0.14	0.24			
	1.5	0.038		0.19	1.10	0.15	0.16	0.25			
	2.0	0.037		0.18	0.96	0.25	0.24	0.30			
120	0.0	0.028	±10	0.28	2.42	0.05	0.12	0.30	0.017		0.02
	0.5	0.024		0.24	1.62	0.05	0.08	0.25			
	1.0	0.022		0.22	1.18	0.10	0.12	0.25			
	1.5	0.021		0.21	0.90	0.15	0.13	0.25			
	2.0	0.021		0.21	0.71	0.25	0.18	0.28			
180	0.0	0.024		0.24	2.90	0.05	0.14	0.28	0.018		0.02
	0.5	0.021		0.21	1.92	0.05	0.10	0.23			
	1.0	0.019		0.19	1.40	0.10	0.14	0.24			
	1.5	0.018		0.18	1.06	0.15	0.15	0.23			
	2.0	0.017		0.17	0.82	0.25	0.20	0.26			

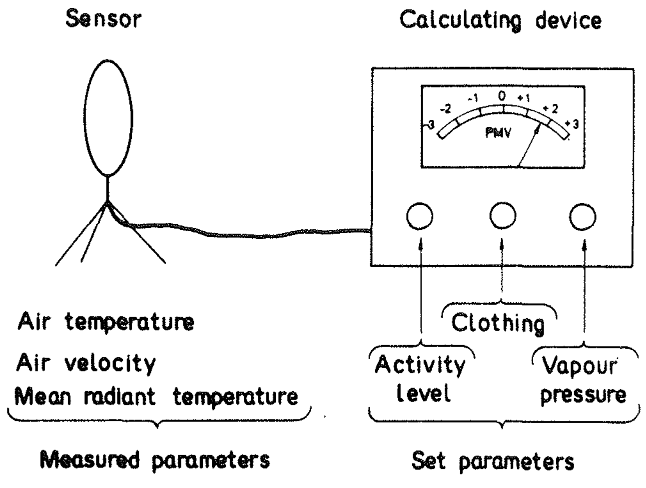

Fig. 1 Principle outline of thermal comfort meter

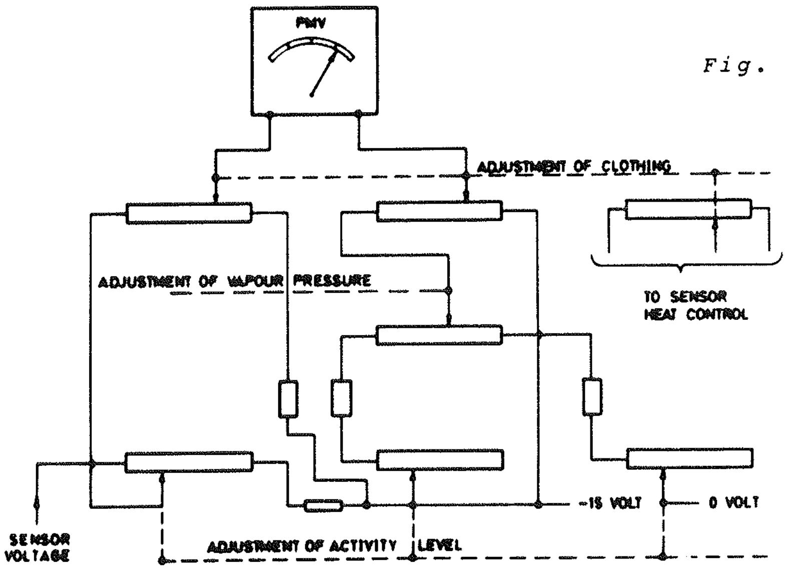

Fig. 2 Analog resistance network for calculating the PMV value from the sensor voltage and the set values of activity level, clothing and vapor pressure

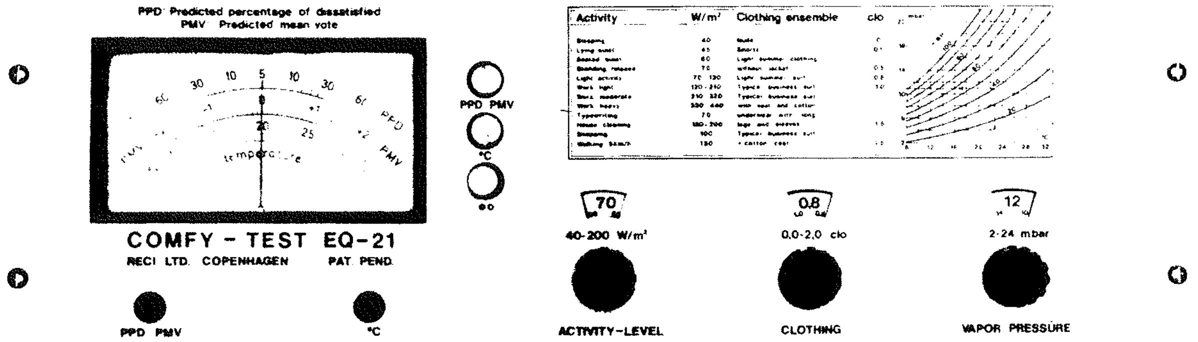

Fig. 3 The control and calculating unit

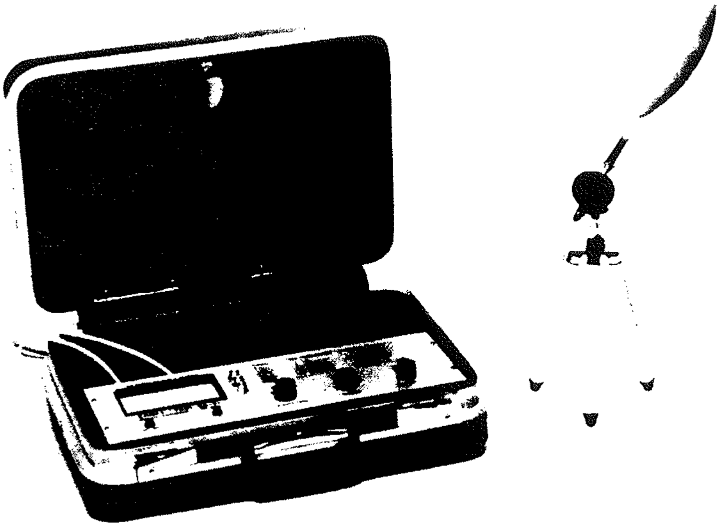

Fig. 4 The Comfy-Test with the sensor on the right

DISCUSSION

PROFESSOR F.H. ROHLES, Kansas State Univ., Manhattan,KS: Have you systematically validated the readings from your meter against responses from people in various environments?

MADSEN: Not systematically. At demonstrations of the comfort meter to an audience of up to one hundred people, I have often asked these people to vote according to Fanger's PMV scale. Before voting, the activity level and the clothing were set at the instrument, and after the voting the measured PMV value was compared with the actual mean voting.

On these occasions there has been a very good agreement between vote and measurement. But, of course this situation is nearly the same every time, about 60 $^{W}/m^2$ and 0.8 - 1.0 clo.

As shown in my paper, there seems to be a good agreement between the PMV values measured with the comfort meter and the values calculated from measurements taken of the different thermal parameters. It seems to me that the correlation between the PMV value and the thermal sensation of persons in different environments is indeed falling within Fanger's sphere.

But, I agree that this instrument--because of its fast response and good reproductivity--would be a good tool to use as a practical check of this correlation.

PROFESSOR CHARLES KIPPENHART, University of Washington, Seattle, WA: What are the spectrol characteristics of the sensor, particularly in the long infrared?

MADSEN: In the long infrared radiation area, the emittance from the sensor is of about 0.96, or nearly the same as that from the human skin, or a black globe.

KIPPENHART: In the aysymetrical radiant field, the globe thermometer, which is quite flat gives a higher PMV. This would be expected if the sensor long infra absorptively were less. Since only instrument readings were compared, how can you say that the comfort meter PVM indication is "better". I would say that this would depend on how the PMV gathered from persons subjected to this environment would vote.

MADSEN: In Table 3A: "Radiation field at a right angle to the sensor's axis", you will find a fairly good correlation between the PMV-values, calculated from globe measurements, and measured with the comfort meter. In this case, the projected area factor between the globe and the radiation source is $(\frac{\cdot\ r^2}{\cdot\ d^2}) = 0.25$, and between the sensor and the radiation source the project area factor is 0.28 (from table 1), or nearly the same.

In Table 3B: "Radiation field along the sensor", you will find a significantly lower PMV-value when using the comfort meter, than you will get from globe measurements. The reason for this difference is that in this case the sensor has a projected area factor at only 0.08 in relation to the radiation source (see table 1), whereas the one of the glove still is of 0.25.

A person standing just below a spotlight, for instance, may have the same small projected area factor in relation to this radiation source, and consequently the spotlight will have only a small influence on his heat loss - and on his PMV-value. A horizontal radiation source of the same intensity will change his heat loss much more on account of the much higher projected area factor of 0.23 - 0.35 (see table 1), and he will thus get a higher PMV-value.

Conclusion: The emittance is of about 0.96 for both globe, sensor, and human being. The shape of the sensor is designed in a way that it has nearly the same projected area factors in different directions as the human being, whereas the globe has the same projected area factor in all directions.

RICHARD PEFLEY, Mech Engr Dept Chairman, Santa Clara Univ., Santa Clara, CA: In a still air environment, sedentary people dictate the convective coefficient by their motions. How is this effect built into the instrument?

MADSEN: You are quite right, at higher activity levels people are moving; the sensor is not. Therefore, I have calculated the analogical resistance network (Fig. 2) so that for higher activity levels (100 - 200 W/m^2) the instrument with the sensor placed in still air will calculate a PMV value corresponding to 0.15 m/s for activity levels of 100-120 and 140 W/m^2 and to 0.2 m/s for 160-180 and 200 W/m^2. In other words, the instrument will calculate a PMV value which is, for higher activity levels, slightly lower than the PMV value corresponding to still air.

NELS JONNES, 3M Co., St. Paul, MN: What are the environmental limits of the comfy-meter? What are the capabilities for heat-stress and for cold-stress environments?

MADSEN: It is difficult to state any exact environmental limits. These are dependent on the actual activity level and clothing. However, I can state the outer limits corresponding to the limitation of the PMV value which can be shown at the meter. They are -2.5 and + 2.5 PMV.

In still air for $40 W/m^2$ and 0.0 clo you will find -2.5 PMV ∿ 28°C; +2.5PMV ∿ 34°C and for 200 W/m^2 and 2.0 clo you will get -2.5 PMV ∿ < - 10°C; +2.5 PMV ∿ 21°C

In situtations of heat stress, there can be some problems at the upper end of the PMV scale on account of the sweat secretion, but in this area we are no longer talking about thermal comfort. In cold stress environments there will be no problems as long as you are able to set the correct clo value at the instrument.

PROFESSOR A. PHARO GAGGE, John B. Pierce Foundation Laboratory, New Haven, CO: We have had some experience using your Comfimeter in the field. During our surveys of office workers in the GSA Building in NYC during summer 1974 and winter 1975, we found the Comfimeter had an "instrumental" sensitivity δ (PMV)/ δT_a of 0.33 ± 0.02 Cat/°C and proved itself as consistent and with a high test-retest reliability coefficient. In comparison, the office people surveyed (approx. 500) by questionnaire showed an overall thermal sensitivity of 0.48 ± 0.04 Cat/°C. These observations might show that these people were slightly more sensitive to changes in the T_a-environment than the Comfimeter when used as the sensing instrument.

We hope in the future that a direct reading of Operative Temperature can be incorporated into the meter. We feel that a T_o measurement is more meaningful in judging Comfort than when T_a and MRT are used individually.

MADSEN: I am very glad indeed to hear that my instrument has been used in the field also here in the U.S.

1. In Fanger's book "Thermal Comfort"[1] on page 124 (see fig.), $\partial PMV/\partial t_a$ is shown for different activity levels, clothings,

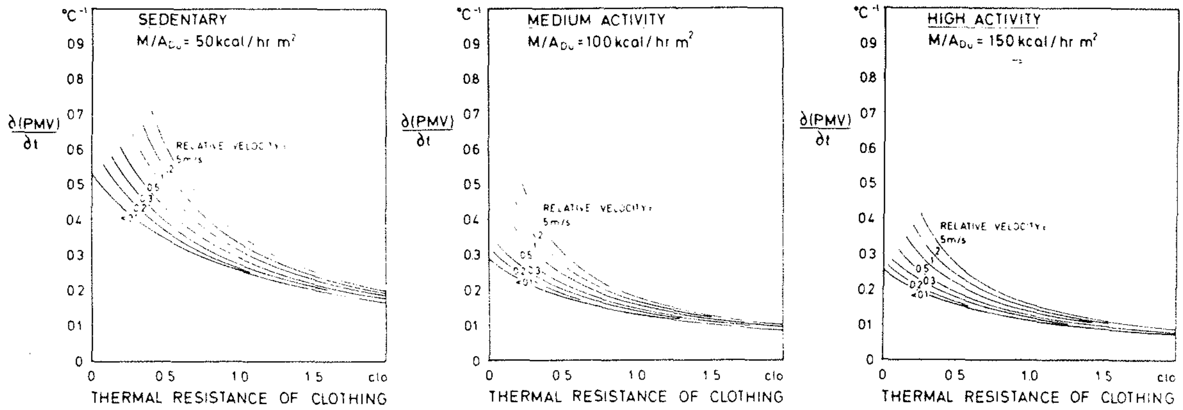

Fig. 23. $\delta(PMV)/\delta t$ as a function of the thermal resistance of the clothing with rel. velocity as parameter, at three different activity levels. $\delta(PMV)/\delta t$ is determined for PMV = 0 and indicates the increment of predicted mean vote, when air temperature (= mean radiant temperature) is increased by 1 C. (Constant vapour pressure.)

and air velocities. For sedentary persons with 0.5 clo and in still air, $\partial PMV/\partial t_a$ = 0.35 Cat/°C. Higher activity levels and higher clo values will give even smaller sensivities. Only a higher air velocity will approach the sensivity to the 0.48 value you found in the GSA Building. But the air velocity must be high (about 1 m/s) in order to get 0.48 Cat/°C, and I don't think the velocity has been that high.

It seems that the meter has been in agreement with Fanger's PMV expression. But your high value for $\partial PMV/\partial t_a$ indicates that there is some discrepancy between the PMV expression and your results. One reason could be that in the GSA Building there has been varying air velocities (turbulences). This can possibly cause a narrowing of the PMV scale, and thereby an increased $\partial PMV/\partial t_a$. There is still a lot of work to do in this field.

2. For the time being, the comfort meter is able to directly measure the equivalent temperature, defined as the equivalent value of air temperature and mean radiant temperature at air velocity nil, which gives the same dry heat loss from a person as the actual combination of these three thermal parameters.

It would be quite simple to modify the instrument for direct measuring of the operative temperature. The sensor has already a temperature-dependent resistance wire around the whole of the surface. By use of this, in a measuring bridge it will be possible to determine the actual mean temperature of the unheated sensor, and as a result of the shape and the radiation properties of the sensor this would be the operative temperature in relation to a human being. I shall try to make this modification of the instrument.