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Draught, Radiant Temperature Asymmetry and Air Temperature – a Comparison between Measured and Estimated Thermal Parameters

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Abstract

Thermal comfort measurements were taken in 17 enterprises at 129 work sites in shops, stores and offices. The measurements included air temperature, air velocity, relative humidity and radiant temperature asymmetry according to ISO 7726 and ISO 7730 standards. The workers also answered a questionnaire dealing with thermal comfort. Predicted mean vote (PMV) and the percentages of workers complaining of draught ("percentage dissatisfied", PD) were determined and compared with the workers' assessments of thermal conditions. The estimations of air temperature were always too low, and the estimated PMV indicated that the thermal environment was too warm. The calculated PMVs were usually lower than the estimated ones. Most of the workers complained of draught, even though, according to the PD index, fewer than 17% of the workers should have felt discomfort due to draught. The radiant temperature asymmetry was always small and did not explain complaints of draught on the basis of the reference value. Judged by the present reference values, and the measurement of the thermal environment, the workers overestimated the sensation of thermal discomfort.

KEY WORDS:
Thermal comfort, Subjective assessment, Temperature asymmetry, Draught, Shops, Offices

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Introduction

Draught is one of the most frequent reasons for complaints of indoor environments. According to a survey by questionnaire among Finnish workers (Central Statistical Office of Finland, 1984) about 16% of all workers complained of draught to a greater or lesser degree. The complaints depended on the nature of their work, however; in construction work about 33% felt draught, in shops and stores about 16% and in offices only 5-10%. High air temperature was a discomfort factor to 7% and low air temperature to 15% of all workers. Unfortunately, the survey did not reveal whether hot or cold surfaces caused discomfort due to radiant temperature asymmetry.

At least four physical parameters should be taken into account in industrial hygiene surveys when workers complain of their indoor thermal climate: air velocity (v_a), air temperature (t_a), mean radiant temperature (t_r) including radiant temperature asymmetry (dt_{pr}), and relative air humidity (RH) or water vapour pressure (P_a). In addition, thermal neutrality depends on personal factors (activity level (M), and thermal insulation of clothing (I_{clo})). The International Standards ISO 7726 and 7730 specify the methods for measuring and evaluating thermal indoor climate. In the United States, the most widely used comfort standard is ASH-

RAE 55-1981. Its requirements are very similiar to those of the ISO standards for thermal environment. In the Nordic countries, the methods of measuring recommended by the work group on indoor climate are also followed (Elnäs et al. 1985). The group included representatives from all the Nordic countries, and the work was financed by the Nordic Council of Ministers. These methods of measuring are based on the ISO standards.

Air currents coming from ventilation and air-conditioning systems or from cold surfaces such as windows may cause a sensation of draught. In these cases air velocity measurements, including mean air velocities and turbulence intensity or standard deviation, should be recorded in addition to air temperatures. In explaining draught, the radiant temperature asymmetry due to cold windows or hot radiators is believed to be an important parameter which can now be measured according to the ISO standard (ISO 7726, 1985).

The aim of the study was to identify the reasons for thermal complaints in shops, stores and offices by measuring thermal parameters such as air velocity, air temperature, radiant temperature asymmetry and relative humidity according to the ISO 7730 standard, and to compare the measured values to the results obtained from the questionnaires filled out by the workers and to the results given by comfort indices.

Material and Methods

Shops, Stores and Offices

The measurements were performed at 129 work sites, situated in 17 enterprises (13 shops and stores and 4 office buildings); except for seven sites in private offices, all were open-plan. Eleven were mechanically ventilated, including inlets and outlets and in some cases also air-conditioning. Six were naturally ventilated, with outlet ducts without fans. The situation represented typical conditions of air temperature, air supply temperature, air change rate and heat supply found in Finnish office buildings, shops and stores (Kovanen et al, 1987; Kähkönen and Ilmarinen, 1987).

Thermal Factors

Thermal parameters of air temperature (t_a), air velocity (v_a), and relative humidity (RH) at the work sites were continuously recorded during one working day using three kinds of indoor climate analyser. The measurements were taken mainly at neck level, i.e. 1.1 m or 1.7 m depending on whether the subject was sitting (mainly office work) or standing (mainly shop work). Thermal climate was assessed by using only neck-level measurements. The indoor thermal climate measurements were carried out according to the recommended ISO 7726 and ISO 7730 standards. The sensors were fixed on a tripod near the worker.

Indoor Climate Analysers

The Brüel & Kjær 1213 Indoor Climatic Analyser measured all the thermal parameters, including radiant temperature asymmetry (Brüel & Kjær, Denmark). One of the faces of the asymmetry transducer was directed towards the window. The incident power on each side of the transducer, radiating from the surrounding surfaces, was also calculated and read out. The measurements were taken at neck level.

The second thermal analyser was constructed using an HP75 portable computer and an HP3421 data acquisition unit (Hewlett Packard, USA). This analyser measured air temperature by using YSI 401 thermistors (Yellow Springs, USA) and air velocity by Disa 54N50 low velocity flow analyser (Dantec electronics, Denmark). Air temperatures were measured at ankle, abdomen and neck levels, but air velocities were measured at neck level only.

The third analyser was a Monitor Labs 9303 data logger (Monitor Labs, USA). Air temperature was measured using copper-constantan thermoelements at neck, abdomen and ankle levels. The air velocity was measured by TSI-1410 hot wire anemometers (TSI-corporation, USA) only at neck and ankle levels. The Hewlett Packard and Monitor Labs analysers measured relative humidity using Vaisala Humicap humidity sensors (Vaisala, Finland), which are based on the capacitance change in a polymer film of thickness 1 µm as it absorbs water.

The sensors of the Brüel & Kjær 1213 Indoor Climatic Analyser and Disa 54N50 Low Velocity Flow Analyser were calibrated by the manufacturer. The thermistors and thermoelements of the other analysers were calibrated in a water bath, and the TSI-anemometers in a wind tunnel. All temperature sensors were shielded against thermal radiation. The accuracy of the instrumentation fulfilled the requirements of the ISO 7726 and ASHRAE standards.

Subjective Ratings

During the measurement of thermal parameters, the workers were asked to fill out a self-administered questionnaire concerning thermal sensation, ventilation, and whether they felt air movement, and if they did feel it, whether it was uncomfortable. The subjects were asked to fill out at least one questionnaire in the morning and one in the afternoon. The workers also graded their thermal comfort according to the PMV scale ("estimated PMV") and estimated the air temperature of their work site in centigrade degrees. Questionnaires of this type are used in laboratory and field surveys in the Nordic countries. If the workers walked around they were asked to stand near the tripod for about 10-15 minutes, i.e the subjects were not moving before answering. They answered how they perceived indoor climate at that time. The number of answers given by women was 205 and that of men only 42.

Clothing Insulation and Metabolic Rate

The thermal insulation of a whole clothing ensemble (I_{cle}) was estimated by summing up the values for individual garments (I_{clu}) using the following equation (Olesen, 1985; ISO-DP 9920, 1988):

$$I_{cle} = \Sigma I_{clu} \qquad (1)$$

Activity level (M) was estimated by means of tables (ISO 7730, 1984) or using the Edholm scale (Edholm, 1966; ISO-DIS 8996, 1987).

PMV and PD Indices

The first requirement for an acceptable thermal environment is that a person feels thermally neutral as regards the whole body, i.e. the person does not know whether he/she would prefer a higher or lower ambient temperature level. This is evaluated by the PMV index. The index is a function of the activity level, clothing insulation, air speed, operative temperature and humidity. The algorithm used in the study is described in detail in the ISO 7730 standard. The predicted mean vote (PMV index) was determined from the measured values of thermal parameters, and the values of M and I_{cle} ("calculated PMV")(ISO 7730, 1984) for every questionnaire given by the workers.

Thermal neutrality as described by the PMV index is not the only condition for thermal comfort. A person may feel thermally neutral for the body as a whole, but may not be comfortable if one part of the body is warm and another cold. It is therefore a further requirement for thermal comfort that no local warm or cold discomfort exists on any part of the body. Such local discomfort may be caused by an asymmetric radiant field, by local convective cooling (draught), and by a vertical air temperature gradient.

The percentage of those who were dissatisfied (PD) due to draught in ventilated working areas (Fanger and Christensen, 1986; Melikov and Fanger, 1989) was calculated using the equation:

$$PD = (34 - t_a)(v - 0.05)^{0.65}(3.14 + 0.37\, v\, T_u) \qquad (2)$$

if $v < 0.05$ m/s then $v = 0.05$ m/s and if $PD > 100\%$ then $PD = 100\%$

where v is mean air velocity (m/s) and t_a air temperature (°C) and T_u is turbulence intensity.

Turbulence intensity was calculated from the values given by the Brüel & Kjær 1213 Indoor Climatic Analyser or Disa 54N50 Low Velocity Flow Analyser.

Mean radiant temperatures (t_r) were calculated from plane radiant temperatures given by the Brüel & Kjær 1213 Indoor Climatic Analyser using the equations:

$$t_r = 0.17(t_{pr}^{+x} + t_{pr}^{-x}) + 0.27(t_{pr}^{+y} + t_{pr}^{-y}) + 0.06(t_{pr}^{+z} + t_{pr}^{-z}) \quad (3)$$

for a standing and

$$t_r = 0.16(t_{pr}^{+x} + t_{pr}^{-x}) + 0.21(t_{pr}^{+y} + t_{pr}^{-y}) + 0.13(t_{pr}^{+z} + t_{pr}^{-z}) \quad (4)$$

for a seated person

where t_{pr} is plane radiant temperature in two opposite directions along the x, y, and z axis. Vertical and horizontal temperature asymmetry was measured if the ceiling, floor and walls were not of the same temperature.

The measured thermal parameters as well as corresponding thermal sensation gradings were first classified according to air temperature into groups: 19.5-20.5, 20.6-21.5, ..., 26.6-27.5 °C and then in each group according to the air velocity: ≤0.075, 0.076-0.125, 0.126-0.175, >0.176 m/s. The classification was similiar to that used by Fanger and Christensen in their comprehensive chamber experiments.

Results and Discussion

The measured thermal parameters and comfort gradings are shown in Table 1 for shops and stores, and in Table 2 for offices. During the studies, the air temperature varied from 20.2 to 26.1 °C in shops and stores and from 21.3 to 24.0 °C in offices. The workers always estimated the air temperature to be 0.3-3.6 °C lower that it actually was. In Finland the recommended indoor air temperature in office buildings or shops and stores is nowadays 20-21 °C. These lower temperatures are preferred because a strong correlation was found between high air temperatures and thermal complaints. Many researchers have also shown that the comfort temperature is lower than that predicted by the comfort equation (Auliciems, 1977; Fishman and Pimbert, 1978, Schiller et al., 1988). From the late seventies onwards the air temperatures in office buildings have gradually increased up to 24-25 °C.

The calculated PMV was 0.0-1.5 and the estimated PMV was -0.3-2.7 in shops and stores. In offices, the calculated and estimated PMVs were from -0.2 to -0.8 and from -0.5 to 1.5, respectively. Considerable individual differences were found, however, between estimated and calculated PMV values. When the temperature at the work site increased, the workers graded the thermal comfort according to the PMV scale as "too warm", although the air temperature was estimated to be lower than the actual value. In offices, the calculated PMV values were lower than the estimated PMV values. The observation is in agreement with the findings of Fishman and Pimbert in 1978, and of Fanger and Christensen in 1986. In the shops and stores this tendency was not so clear between the calculated and estimated PMV values when the air temperature was less than 24 °C. In this case, thermal votes may be affected by cold airflows due to opening the door. The cold airflows sometimes caused rapid changes in air temperature. Knudsen and Fanger recently showed that during temperature down-step, thermal sensation votes dropped immediately to a level cooler than the later steady-state sensation (Knudsen and Fanger, 1990). It is recommended that the predicted percentage of persons who are

Table 1 The results of thermal parameters of indoor climate in shops and stores. Mean and standard error of mean.

T_a °C Measured	T_a °C Estimated	PMV Calculated	PMV Estimated	I_{clc} clo	RH %	V_a m/s	T_u %	PD	S_{dr} %	U_c %	T_{pr} °C	dt_{pr} °C	Inc W/m²	N
20.2±0.1	19.1±0.5	0.2±0.3	0.6±0.5	0.89±0.02	32	0.05	73±8	0.9±0.6	100	50	-	-	-	8
20.2±0.1	18.0±1.5	0.8±0.1	0.0±0.9	1.00±0.05	30	0.10	31±9	7.2±1.0	100	40	-	-	-	4
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
21.1±0.1	18.9±0.4	0.2±0.2	0.3±0.3	0.69±0.06	33	0.05	59±7	1.9±0.5	100	44	22.7±0.2	-0.9±0.3	434±1	16
21.3±0.1	18.9±0.7	0.2±0.3	0.1±0.3	0.72±0.04	34	0.10	32±3	8.1±0.7	89	33	22.7±0.2	-1.0±0.2	436±1	9
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22.1±0.1	19.4±0.4	0.6±0.1	0.6±0.3	0.70±0.03	34	0.05	63±4	1.5±0.4	74	42	23.0±0.2	-1.4±0.4	434±1	19
22.1±0.1	19.4±0.4	0.5±0.1	0.4±0.3	0.59±0.03	34	0.10	42±5	7.7±0.4	80	27	24.4±0.3	-1.3±0.1	442±2	15
22.3±0.1	22.8±0.9	0.6±0.1	0.2±0.4	0.48±0.03	33	0.15	26±6	12.2±0.4	100	50	24.6±0.3	-1.5±0.2	445±3	6
23.2±0.1	20.0±0.4	0.5±0.1	0.2±0.2	0.58±0.03	34	0.05	52±5	0.7±0.3	59	50	23.9±0.3	-1.0±0.3	429±2	22
22.8±0.1	19.9±0.7	0.8±0.1	0.9±0.4	0.56±0.03	28	0.10	50±6	9.0±0.8	40	0	22.9±0.5	-0.7±0.2	436±1	10
22.9±0.1	21.5±1.5	1.5±0.4	-0.3±0.7	0.61±0.08	27	0.15	51±4	17.0±1.0	67	33	23.8±1.0	-1.2±0.4	442±3	3
24.1±0.1	21.1±0.7	1.0±0.1	1.1±0.4	0.57±0.06	31	0.05	79±9	0.0±0.0	38	0	23.9±1.0	-1.5±0.6	441±6	8
24.1±0.1	22.2±0.9	0.7±0.2	1.0±0.3	0.52±0.03	31	0.10	41±5	6.2±0.5	10	0	24.4±0.5	-0.6±0.1	442±2	10
24.3±0.1	23.2±0.6	0.8±0.2	1.8±0.3	0.54±0.07	33	0.15	53±4	13.1±1.0	22	22	26.6±0.7	-1.1±0.1	458±4	9
25.3±0.1	22.0±0.1	0.4±0.3	2.7±0.3	0.49±0.06	37	0.05	38±7	1.0±1.0	33	0	25.2±1.7	-1.0±0.4	433±1	3
24.8±0.1	23.1±0.8	0.0±0.3	1.4±0.4	0.45±0.02	33	0.10	57±8	6.7±0.4	29	29	24.7±0.5	-0.6±0.1	446±2	7
25.0±0.1	24.7±1.4	0.6±0.6	1.8±0.2	0.50±0.10	36	0.15	57±1	14.0±0.7	66	66	24.4±0.6	-0.5±0.1	445±4	3
25.9±0.1	24.8±0.5	0.8±0.2	1.8±0.3	0.49±0.03	37	0.05	50±7	1.0±0.5	33	22	26.9±0.1	-0.9±0.2	459±1	9
26.1±0.1	25.8±1.0	1.3±0.1	1.8±0.2	0.54±0.04	39	0.10	51±4	7.3±0.4	0	0	24.5±0.9	-0.6±0.1	444±5	6
-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

T_a = air temperature, PMV = predicted mean vote, I_{clc} = thermal insulation of clothing, RH = relative humidity, V_a = air velocity, T_u = turbulence intensity, PD = percentage of dissatisfied due to draught, S_{dr} = sensation of draught, U_c = Uncomfortable draught, t_{pr} = plane temperature asummetry, dt_{pr} = radiant temperature asymmetry, Inc = incident power, N = number of subjects. The data are classified according to air temperature and air velocity. Metabolic rate 70-125 W/m².

Table 2 The results of thermal parameters of indoor climate in offices. Mean and standard error of mean.

°C T_a	°C T_a	PMV	PMV	clo I_{clo}	% RH	m/s V_a	% T_u	PD	% S_{dr}	% U_c	°C t_{pr}	dt_{pr} °C	Inc W/m²	N
Measured	Esti-mated	Calcu-lated	Esti-mated											
21.3±0.1	20.9±0.4	-0.8±0.1	-0.5±0.3	0.67±0.06	25	0.10	56±8	11.5±1.0	50	33	17.0±0.3	-4.2±0.3	400±1	6
22.4±0.1	19.5±0.6	-0.7±0.1	-0.2±0.2	0.57±0.04	29	0.05	83±7	2.1±1.2	40	20	23.1±0.2	0.4±0.2	436±2	5
22.4±0.1	20.6±0.7	-0.5±0.1	-0.2±0.3	0.74±0.06	19	0.10	51±8	9.2±0.8	57	57	22.4±0.2	-1.7±0.7	428±4	7
22.2±0.2	21.3±0.9	-0.7±0.2	-0.3±0.3	0.66±0.07	27	0.15	55±8	14.9±1.2	33	0	22.1 ±0.7	-0.6±0.7	431±5	3
23.2±0.1	21.3±0.5	-0.4±0.1	0.3±0.3	0.60±0.03	24	0.05	55±7	2.0±0.5	83	83	23.0±0.1	0.0±0.2	435±1	18
23.1±0.5	21.6±0.6	-0.2±0.1	1.2±0.1	0.73±0.03	23	0.10	54±2	7.9±0.4	62	48	23.3±0.2	0.1±0.2	438±1	29
23.8±0.1	20.2±0.8	-0.5±0.1	0.0±0.3	0.46±0.01	23	0.05	41±8	2.1±0.9	100	80	-	-	-	5
24.0±0.1	23.0±0.5	-0.2±0.1	1.5±0.3	0.62±0.06	25	0.10	50±9	9.0±1.0	42	0	23.8±0.4	-0.8±1.6	439±6	7

T_a = air temperature, PMV = predicted mean vote, I_{clc} = thermal insulation of clothing, RH = relative humidity, V_a = air velocity, T_u = turbulence intensity, PD = percentage of dissatisfied due to draught, S_{dr} = sensation of draught, U_c = uncomfortable draught, t_{pr} = plane temperature asymmetry, dt_{pr} = radiant temperature asymmetry, Inc = incident power, N = number of subjects. The data are classified according to air temperature and air velocity. Metabolic rate 70-125 W/m².

dissatisfied due to a general warm or cold sensation should be less than 10% (ISO 7730). This corresponds to a criterion of -0.5 < PMV < 0.5 for the PMV index. The calculated PMVs fulfilled the criterion up to 23-24 °C quite well in shops and stores, but in offices the PMVs were "slightly cool". In a warmer environment in shops and stores the proportion of workers who felt thermal discomfort increased to 15-38%.

The thermal insulation of clothing ensembles varied from 0.89 clo at air temperature 20.2 °C down to 0.49 clo at air temperature 25.9 °C in shops and stores. In offices, thermal insulation was 0.46-0.74 clo. The insulation was about 0.1-0.2 clo lower than in Fanger and Chistensen's experiments, in which clothing insulation was modified by the subjects to feel thermal neutrality. The thermal insulation of clothing ensembles corresponds to the assumption of ISO standard (ISO 7730, 1984) which assumes insulation of 0.5 clo in summer and 1.0 clo in winter.

The mean relative humidity was 23-39%. In winter, however, the relative humidity was as low as 10-15%, but relative humidity has only a small effect on thermal comfort. The relative humidity was usually estimated as "dry" or "normal", but individual ratings differed greatly. During the winter, in order to save in the consumption of energy, humidifiers were usually not used.

The mean air velocity was 0.05-0.15 m/s and turbulence intensity was 26-79% in shops and stores, and in offices 0.05-0.15 m/s and 41-83%, respectively. The mean air velocities were in the same range as in Fanger and Christensen's study. However, higher turbulence intensities than those reported by Melikov et al. and Fanger and Christensen, were observed in this study. According to ISO 7730 standard the mean air velocity should be less than 0.15 m/s in winter and 0.25 m/s in summer. Mean air velocities very rarely exceeded the standard's maximum (Kovanen et al., 1987; Schiller et al., 1988; Kähkönen and Ilmarinen, 1987). When the air temperature was 20-21 °C almost all the workers felt air movement, and 33-50% of them experienced the air movement as uncomfortable. At air temperatures of 22-23 °C about 33-100% of the workers sensed air movement, and 0% to 83% of these experienced the air movement as uncomfortable, depending on the building tested. At a temperature of 24-26 °C all the workers were able to sense air movement, and 0% to 80% of them experienced it as uncomfortable. Because of the small number of votes in some groups, it was not possible to determine accurately whether the workers sensed air movements and felt them to be uncomfortable. However, the PD index predicted that, under the thermal conditions studied, less than 17% of the workers should feel the velocity-related discomfort. The results of the questionnaires concerning draught were very uncertain both in shops and offices, and there was a surprisingly great difference between estimated and calculated values.

The mean radiant temperature asymmetry ranged from -0.4 to -1.5 °C in shops and stores. The greatest asymmetry was +5 °C during the summer. In this case the sun was shining through the window to which the sensor was directed. The greatest asymmetry in offices was -4.2 °C at a work site which was situated 0.8 m from a large cold window. Usually asymmetry was from 0 °C to -1.7 °C. The values are surprisingly low compared to 10 °C reference values (ISO 7730, 1984; ASHRAE 55-81, 1981). The observation is in agreement with that made by Schiller et al. in 1988. They also observed that horizontal radiant temperature asymmetry occurred only on very rare occasions. However, the recommendations of the standard are only guidelines regarding the radiant temperature asymmetry. In winter the cold surfaces were windows with a surface temperature of 14-18 °C and the only warm surfaces were heaters. However, these surfaces were usually behind curtains, shelves, furniture, etc., which reduce the angle factor and the effect of thermal radiation on man. The difference between air temperature (t_a) and mean radiant temperature (t_r) was very small and ranged from 0 °C to 0.3 °C. In order to increase surface temperatures, triple pane windows were used, and outdoor and indoor window frames were thermally insulated. This construction technique reduced temperature asymmetry due to windows. The workers were not asked whether the sensation of draught was due to radiant temperature asymmetry or to airflow.

Conclusion

Complaints of thermal climate in office buildings and shops and stores were very common. In winter the complaints were mainly due to draught, low air temperatures and cold airflows. In summer, during the hottest weeks, the workers complained of high air temperatures. According to the questionnaire, however, the subjects estimated systematically the air temperatures to be lower than the measured values. Subjective ratings concerning draught were very uncertain, and "negative" compared to calculated values based on laboratory studies. Mean radiant temperature was approximately equal to the air temperature, and the small difference did not explain the draught discomfort. It seems, however, that more people suffer from draught in practice than predicted by the PD index. The calculated PMV values were usually lower than PMV estimations. The temperature asymmetry was far below the reference values and its effect on the draught complaints should be minimal in an office type environment, or it may be that workers are much more sensitive to radiant temperature asymmetry than presently believed. It seems that by direct questions concerning thermal parameters it is difficult to get a sufficiently objective picture about the thermal climate of workplaces. This in turn may lead to the overemphasis of thermal complaints. An opinion leader may also affect the psychological work climate and the majority tend to vote according to general opinion. On the other hand, the thermal environment is estimated by using mean values of the thermal parameters and the indices which are based on regression analysis; these do not take into account the individual differences of the workers.

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