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Building and Environment, Vol. 25, No. 4, pp. 309–316, 1990.
Printed in Great Britain.

0360–1323/90 $3.00+0.00

Literature Review on Thermal Comfort in Transient Conditions

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The conventional theory of thermal comfort in conditions characteristic for dwellings and offices (for example, that of Fanger) assumes steady-state conditions. Yet thermal conditions in buildings are seldom steady, due to the interaction between building structure, climate, occupancy, and HVAC system. This article reviews work on thermal comfort specifically undertaken to examine what variations in indoor temperatures may be acceptable.

Following an account of man's thermoregulatory system, some experimental findings on periodic and on ramp (or drift) variation in room temperature are presented.

It is concluded that the results for cyclic variations uphold the present ASHRAE standard, but those for drifts may not.

1. INTRODUCTION

THERMAL COMFORT is generally defined as that condition of mind which expresses satisfaction with the thermal environment [1]. Dissatisfaction may be caused by the body being too warm or cold as a whole, or by unwanted heating or cooling of a particular part of the body (local discomfort).

From earlier research [2–4] we know that thermal comfort is strongly related to the thermal balance of the body. This balance is influenced by:

- Environmental parameters like: air temperature (T_a) and mean radiant temperature (T_r),† relative air velocity (v) and relative humidity (rh)
- Personal parameters like: activity level or metabolic rate (M) (units: 1 met = 58 W m^{-2}) and clothing thermal resistance (I_{cl}) (units: 1 clo = 0.155 m^2 K W^{-1}).

Extensive investigations and experiments involving numerous subjects have resulted in methods for predicting the degree of thermal discomfort of people exposed to a still thermal environment. The most well known and widely accepted methods are: (1) Fanger's "Comfort Equation" and his practical concepts of "Predicted Mean Vote" and "Predicted Percentage of Dissatisfied" [2]; (2) the J. B. Pierce two-node model of human thermoregulation [4, 5]. With these methods several thermal comfort standards [1, 6–8] have been established during the past decade. These standards specify environmental parameter ranges (i.e. comfort zones) in which a large percentage of occupants (generally at least 80%) with given personal parameters will regard the environment as acceptable.‡ Most work related to thermal comfort has concentrated on steady-state conditions. This is expressed by the fact that only one of the above standards [7] also specifies limits for changing environmental parameters (for T_o only).

Because of the thermal interaction between building structure, occupancy, climate and HVAC system, pure steady-state conditions are rarely encountered in practice. For example, Madsen [9] found indoor temperature fluctuations between 0.5 and 3.9°C (during 24 h with a constant set point) which depended on the combination of heating and control system.

Sometimes it may even be advantageous to allow the environmental conditions to change. This was demonstrated in a field experiment [10] where it was found that decreasing the acceleration heating of the room thermostat in a dwelling resulted in a lower fuel consumption. This led however to considerably increased variations in indoor temperature, but it was not clear at the time whether these fluctuations would be acceptable or not to inhabitants.

This is the background to the present literature study on thermal comfort in transient conditions. We know that temperature is the most important environmental parameter with respect to thermal comfort, so this study focused mainly on the effects of changes in temperature and mainly in homes, offices, etc.

In Section 2 man's thermoregulatory system is discussed so as to show the interaction between man, building and HVAC system. Our present understanding of human thermoregulatory mechanisms however is not sufficient for us to predict with confidence our response to time-varying stimuli and recourse must be had to controlled tests. The results of such work on cyclically varying temperatures are present in Section 3.1 and on other types of changes in the following section. Finally in Section 4 some conclusions towards practical applications are made.

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† T_a is often combined with T_r to form operative temperature ($T_o = aT_a + (1-a)T_r$ where $a < 1$).

‡ For example, ISO [1] recommends for light, mainly sedentary activity during winter conditions (heating period): "(*a*) *The operative temperature shall be between* 20 *and* 24°C (*i.e.* 22±2°C). (*b*) ..."; and during summer conditions (cooling period): "(*a*) *The operative temperature shall be between* 23 *and* 26°C (*i.e.* 24.5±1.5°C). (*b*) ...";

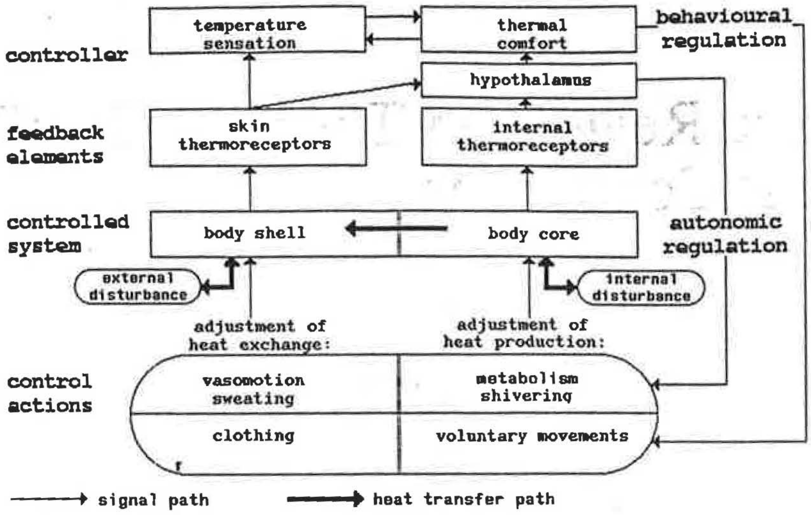

Fig. 1. Schematic diagram of autonomic and behavioural temperature regulation in man (modified from Hensel [11]).

2. MAN'S THERMOREGULATORY SYSTEM

The human body produces heat (principally by metabolism—i.e. oxidation of food elements), exchanges heat with the environment (mainly by radiation and convection) and loses heat by evaporation of body fluids. During normal rest and exercise these processes result in average vital organ temperatures near 37°C. The body's temperature control system tries to maintain these temperatures when thermal disturbances occur. According to Hensel [11], who studied a vast amount of literature on the subject, man's thermoregulatory system is more complicated and incorporates more control principles than any actual technical control system. It behaves mathematically in a highly non-linear manner and contains multiple sensors, multiple feedback loops and multiple outputs.

Figure 1 shows some basic feature's of man's thermoregulatory system. The controlled variable is an integrated value of internal temperatures (i.e. near the central nervous system and other deep body temperatures) and skin temperatures. The controlled system is influenced by internal (e.g. internal heat generation by exercise) and external (e.g. originating from environmental heat or cold) thermal disturbances. External thermal disturbances are rapidly detected by thermoreceptors in the skin. This enables the thermoregulatory system to act before the disturbances reach the body core. Important in this respect is the fact that the thermoreceptors in the skin respond to the temperature as well as to the rate of a temperature change. According to Madsen [12] the latter is actually done by sensing heat flow variations through the skin.

Autonomic thermoregulation is controlled by the hypothalamus. There are different autonomic control actions such as adjustment of: heat production (e.g. by shivering), internal thermal resistance (by vasomotion; i.e. control of skin blood flow), external thermal resistance (e.g. by control of respiratory dry heat loss), water secretion and evaporation (e.g. by sweating and respiratory evaporative heat loss). The associated temperatures for these autonomic control actions need not necessarily be identical nor constant or dependent on each other.

Besides autonomic thermoregulation there is also behavioural thermoregulation with control actions such as active movement and adjustment of clothing. According to Hensel [11], behavioural thermoregulation is associated with conscious temperature sensation as well as with thermal comfort or discomfort. The difference between temperature sensation and thermal comfort is that temperature sensation is a rational experience that can be described as being directed towards an objective world in terms of "cold" and "warm". Thermal comfort on the other hand is an emotional experience which can be characterised in terms of "pleasant" and "unpleasant". As McIntyre [3] points out, the meaning of words like "pleasant" and "comfortable" do not have an absolute value, but will be relative to experience and expectation.

Hensel [11] found that temperature sensations (especially local cold sensations) depend mainly on the activity of thermoreceptors in the skin whereas thermal comfort or discomfort reflects a general state of the thermoregulatory system (though this does not imply that changes in thermal comfort are always slower than changes in thermal sensation, as will be seen later on). The condition of thermal comfort is therefore sometimes defined as a state in which there are no driving impulses to correct the environment by behaviour [13]. This is a more objective definition than the ISO definition.

According to McIntyre [3], it is conventional to treat overall thermal discomfort (a subjective condition) in terms of thermal sensation (an objective quantity). This may be justifiable in case of steady-state conditions however probably not when transient conditions have to be judged. The difference between thermal comfort and temperature sensation during changing environmental conditions was clearly demonstrated by experiments of Gagge *et al.* [14]. They exposed subjects for one hour to neutral thermal conditions (29°C), then a step change to a much colder (17.5°C) or warmer (48°C) environment for a two hour exposure, which was followed by a step back to neutral conditions. On entering the cold conditions there were immediate reports of cold sensations and discomfort. On returning to the neutral environment discomfort almost immediately disappeared, while temperature sensations lagged considerably behind the comfort reports and did not return to neutral for all subjects during the one hour post-exposure period. The transient exposures to the hot environment showed much the same responses. On entering the hot conditions there were immediate reports on warm sensations and discomfort. On re-entering the neutral conditions discomfort disappeared rapidly however more slowly than in the case of the cold to neutral step. The temperature sensations showed an overshoot with some initial reports of slightly cool.

In the past much work has been done aimed at finding practical methods for predicting the effects of a particular thermal environment in terms of comfort or discomfort. Reviews and summaries of this were made by Hardy [15], Fanger [2], Benzinger [13], McIntyre [3] and ASHRAE [16]. From these references it is clear that there is much evidence (from steady-state experiments) for cold discomfort being strongly related to mean skin temperature and that warmth discomfort is strongly related to skin wettedness caused by sweat secretion. These relations are the basis for methods like Fanger's [2] Comfort Equation and the work of Gagge *et al.* [4, 5]. In a recent evaluation by Doherty and Arens [17] it was shown that these models are accurate for humans involved in near-sedentary activity and steady-state conditions.

From the fact that the skin thermoreceptors not only sense temperature but also the rate of temperature change and that thermal comfort depends on an integrated value of central and peripheral temperatures, it may be concluded that skin temperature alone is unlikely to be an adequate index for cold discomfort in transient conditions. Because sweat secretion reflects the general state of the thermoregulatory system, skin wettedness is probably a more adequate predictive index for warmth discomfort in transient conditions than mean skin temperature is for cold discomfort. No experimental proof of this has been found however. From these observations one may conclude that the above mentioned essentially steady-state methods are probably not adequate for predictions regarding thermal comfort in transient conditions.

A number of models for simulation of the dynamic behaviour of man's thermoregulatory system have been developed in the past. A well known example is the model of Stolwijk [18] which was later expanded by Gordon [19]. In this model the human body is divided into a large number of segments (originally 24 and in Gordon's version 140) linked together via the appropriate blood flows. Each segment represents volume, density, heat capacitance, heat conductance, metabolism and blood flow of a certain part of the body. The temperature and rate of change of temperature of each segment is available as an input into the controlling system, and any effector output from the controlling system can be applied to any part of the controlled system.

The main application field for this kind of model is research on body temperature regulation itself. No model has been developed which also predicts whether a particular thermal environment is thermally uncomfortable and to what degree. It may be possible to link a model of this kind with the present knowledge on temperature sensation and thermal comfort, so as to enable comfort predictions to be made for transient conditions. This is however beyond the scope of the present study.

From the above discussion it follows that at present there is no other source except results of thermal comfort experiments to assess the acceptability of changing environmental conditions.

3. EXPERIMENTS

A large number of experiments have been conducted on man's response to the thermal environment. Concerning the objectives of the experiments, distinction can be made between investigations on the thermoregulatory system on the one hand and the establishment of thermal comfortable or acceptable conditions on the other hand. The latter type of experiments are primarily of interest in the present study.

Although most work has been concentrated on steady-state conditions, some experiments have examined transient conditions. In principle any of man's last heat balance variables (T_a and T_r or T_o, v, rh, M and I_{cl}) may change in time. However in most cases, changing ambient temperatures has been of interest. Changes can be categorised as:

- Cyclical: triangular or sinusoidal changes in the transient variable (e.g. resulting from the deadband of the HVAC control system), characterised by mean value, peak to peak amplitude and fluctuation period or frequency*
- Ramps or drifts: monotonic, steady changes with time. Ramps refer to actively controlled changes and drifts to passive changes (as one might encounter in a building with no active temperature control). These changes are characterised by starting value, amplitude and rate of change
- Steps, such as one experiences in going from one thermal environment to another. Step changes are described by starting value, direction and amplitude.

The following section describes the results of the most important thermal comfort experiments with cyclical temperature changes since these are primarily of interest in the present context. The next section describes results of some other related experiments. All results relate to environmental conditions in or near the comfort zone for sedentary or slightly active persons wearing normal indoor clothing.

3.1. *Cyclical temperature changes*

Sprague and McNall [20] conducted experiments aimed at providing data, obtained under controlled conditions, as a basis for confirming or modifying existing specifications on fluctuating thermal conditions. Before, these specifications were largely based on field experience.

* With triangular changes, peak-to-peak amplitude ΔT_{ptp}, cycle frequency CPH and rate of temperature $\delta T/\delta t$ are related according to : $\delta T/\delta t = 2 \cdot CPH \cdot \Delta T_{ptp}$ K h^{-1}.

Their first series of tests were designed to study the effect of fluctuating dry bulb temperature on the thermal sensation of sedentary persons ($N = 192$; college age; $M = 1.2$ met; $I_{cl} = 0.6$ clo; $T_r = 25.6°C$; $rh = 45\%$; $v < 0.15$ m s^{-1}). The dry bulb temperature varied according to a triangular wave form with average fluctuation rates in the range 1.7 to 10.9 K h^{-1} and peak to peak amplitudes ranging from 0.6 to 3.3 K, resulting in 1.0 to 2.0 cycles h^{-1}. All tests started from the middle of the comfort zone (mean dry bulb temperature was 25.6°C).

Although it is not clear how acceptability was defined the authors concluded that no serious occupancy complaints should occur due to dry bulb temperature fluctuations if $\Delta T_{ptp}^2 \cdot CPH < 4.6\ K^2\ h^{-1}$ in which ΔT_{ptp} is the peak to peak amplitude of the temperature fluctuation and CPH is the cycle frequency (cycles h^{-1}). This expression, which was only validated inside the comfort zone and for two fluctuation rates, suggests that ΔT_{ptp} could be large for slow fluctuations and that ΔT_{ptp} would have to be small when fluctuations are rapid. This result looks strange; when the human body is regarded as one or more thermal capacitances, one would expect opposite results (i.e. increasing acceptable ΔT_{ptp} with increasing fluctuation rate). Therefore, results like this must be related to the thermoregulation control mechanisms and indicate that the rate of change of temperature is very important.

The authors specifically state that their expression does not apply to systems where the mean radiant temperature fluctuates, since the effect of varying radiant temperatures was not investigated. However, assuming [1, 7] that, at air speeds of 0.4 m s^{-1} or less, the operative temperature is simply the arithmetic mean of dry bulb temperature and mean radiant temperature, the relation between maximum acceptable peak to peak amplitude and cycle rate of operative temperature can be assumed to be $\Delta T_{ptp}^2 \cdot CPH < 1.2\ K^2\ h^{-1}$.

Following these results the tolerated range of temperatures decreases with increasing fluctuation rates. This seems to be contradicted by work of Wyon *et al.* [21] who performed experiments in which the amplitude of the temperature swings was under the subjects' control. They found that subjects tolerated greater amplitudes when the temperature changed more rapidly. In their view this was due to purely physical reasons, as rapid changes of ambient temperature cause skin temperature, and hence thermal sensation, to lag further behind in time and this effectively reduced the experienced temperature fluctuations. It was also found that subjects tolerated greater amplitudes when performing mental work than when resting. McIntyre and Griffiths [22] later pointed out that due to a much smaller rate of change of the mean radiant temperature, when compared with the air temperature, and unusual acceptability criteria (spontaneous dial voting when the temperature was too hot or too cold) the tolerated range in operative temperature was actually smaller than normally found in steady-state conditions.

Later experiments of Wyon *et al.* [23] were designed to investigate the effects on comfort and performance of predetermined ambient temperature swings under more normal working conditions. The subjects ($N = 16$; student age; $M = 1.2$ met; $I_{cl} = 0.6$ clo; $v < 0.1$ m s^{-1}) were exposed to sinusoidal swings around the average preferred ambient temperatures with peak to peak amplitudes in the range 2–8 K and periods ranging from 32 to 8 min (i.e. 1.9–7.5 cycles h^{-1}), resulting in fluctuation rates between 15 and 60 K h^{-1}. Certain complications resulted in considerable damping (up to 75%) of the amplitude of the temperature swings below head level. Also the actual amplitudes of the mean radiant temperatures were lower than half of the intended amplitudes. The authors state that for these reasons the experiments are probably best regarded as an investigation of air temperature swings at head height. From the results they concluded: "*Large temperature swings ... cause increased discomfort*" and "*Large ambient temperature swings appear to have a stimulating effect that is to be preferred to the apparently opposite effect of small temperature swings, but a constant, optimally comfortable temperature, where this can be achieved, would still seem to be preferable to either*". To be able to compare these results with the other references, Wyon's raw data was examined. This revealed that 80% of the votes were in the comfort zone for all swings with intended peak to peak amplitudes of 4 K or less. As indicated above this actually suggests maximum acceptable peak to peak amplitudes of operative temperature fluctuation for the whole body in the range 1–2 K.

Experiments with large ambient temperature swings were also conducted by Nevins *et al.* [24]. The subjects ($N = 18$; different ages; $M = 1.2$ met; $I_{cl} = 0.6$ clo; $rh = 50\%$; $v = 0.25$ m s^{-1}) were exposed to ambient temperature ($T_a = T_r$) swings with a peak-to-peak amplitude of 10 K and an average fluctuation rate of 19 K h^{-1} (0.9 cycles h^{-1}). The mean ambient temperature was 25°C. From the results it was concluded that the preferred ambient temperatures for comfort agreed well with the results of earlier steady-state experiments (on which, for instance, ASHRAE [25] is based) and that there was no clear evidence of an increased or decreased range of acceptable ambient temperatures due to fluctuation. An examination of Nevins' raw data however suggests a maximum acceptable peak-to-peak amplitude of about 2.8 K. This is a little less than the width of the comfort zone for steady-state conditions. It should be noted that when unacceptable temperatures are left out, a rate of temperature change of 19 K h^{-1} would have resulted in a fluctuation frequency of about 3.4 cycles h^{-1} or alternatively 0.9 cycles h^{-1} would have resulted in an average rate of change of 5 K h^{-1}.

Rohles *et al.* [26] conducted a series of experiments in which the subjects ($N = 804$; college age; $M = 1.2$ met; $I_{cl} = 0.6$ clo; $rh = 50\%$) were exposed to cyclical changes around various basal temperatures (17.8–29.4°C) with different amplitudes (1.1 to 5.6 K) at rates ranging from 1.1 to 4.4 K h^{-1} (0.3 to 1.5 cycles h^{-1}). The results showed that if (steady-state) temperature conditions for comfort are met, the thermal environment will be acceptable, for near-sedentary activity while wearing summer clothing, if the rate of changes does not exceed 3.3 K h^{-1} and the peak-to-peak amplitude is equal to or less than 3.3 K (which is approximately the same as the width of the steady-state comfort zone). The discussion following the presentation of the results revealed some criticism which was acknowledged by the authors. Apparently, their acceptability criteria were less coarse than usual. Due to the heat capacity of the building fabric, the mean radiant temperature swings were damped and delayed when the air temperature cycled. For this reason the acceptable maximum rate of change and peak-to-peak amplitude of operative temperature will probably be lower than the values mentioned above.

There are a number of difficulties which should be noted when comparing the results of the above mentioned experiments:

- The results are in fact subjective responses of a highly complex system of which we most probably do not yet know all the processes involved to the extent necessary for controlling all relevant parameters during experiments
- Usage of different semantic voting scales, both in type (i.e. directed towards acceptance (with words like acceptable and unacceptable), comfort, sensation or mixed) and appearance (e.g. 2, 7 or 9 point, and discrete or continuous)
- Differences in acceptability criteria (e.g. comfort interval on a 7 point semantic comfort scale defined as centre-point ± 1.0 vote as opposed to centre-point ± 0.5 votes) which is sometimes unavoidable because of the scale differences
- Differences in conditions: subjects resting or performing mental work, fluctuating dry bulb temperature or fluctuating operative temperature
- Differences in subjects; our knowledge of the distribution of thermoregulatory efficiency (and thus the time factor in discomfort) among people is still very limited and this can easily lead to sample errors.

Regardless of these differences all results seem to indicate that with cyclical fluctuating ambient temperatures the bandwidth of acceptable temperatures decreases with increasing fluctuation frequency. This bandwidth seems to be at its maximum in steady-state conditions. This can be seen in Fig. 2 which comprises the major results of the experiments and indicates which fluctuation frequencies were investigated.

The results suggest that there is a certain amplitude threshold (at about 1 K) below which the influence of fluctuation frequency is negligible. At frequencies below approximately 1.5 cycles h^{-1} the maximum acceptable peak-to-peak amplitude increases with decreasing frequency until the steady-state comfort bandwidth is reached.

As shown in Fig. 2 the results seem to be quite adequately described by ASHRAE's standard 55 [7] which states with regard to cycling temperature: "*If the peak variation in operative temperature exceeds* 1.1 *K the rate of temperature change shall not exceed* 2.2 *K/h. There are no restrictions on the rate of temperature change if the peak-to-peak is* 1.1 *K or less.*" The maximum rate of temperature change of about 2.2 K h^{-1} can be regarded as conservative when compared with the experimental results.

3.2. *Other changes*

Comfort experiments involving temperature drifts or ramps are reported by McIntyre and Griffiths [22], Berglund and Gonzalez [27, 28], Berglund [29] and Rohles *et al.* [30]. From the results it may be concluded that slow temperature changes up to about 0.5 K h^{-1} have no influence on the width of the comfort zone as established under steady-state conditions.

McIntyre and Griffiths [22] report no difference between temperature changes of 0.5, 1.0 and 1.5 K h^{-1} nor steady-state with respect to permissible deviations from neutral temperature.

Berglund and Gonzalez [27] found however that with faster rates of temperature change (i.e. 1.0 and 1.5 K h^{-1}) the permissible deviation from neutral temperature was larger than was the case for the 0.5 K h^{-1} temperature change. This difference was more pronounced for subjects wearing summer clothing (0.5 clo) than for those wearing warmer clothing (0.7 or 0.9 clo). It should be mentioned however that these authors used an unusual assessment of acceptability. Instead of the more common procedure of deriving acceptability indirectly from comfort votes, a direct two point acceptability question was used. This resulted in a considerably wider ambient temperature zone where the acceptability of the subjects was 80% or higher when compared to the usual comfort zones. Also the acceptable zone was shifted somewhat to the warm side, implying that a slightly warm environment is more acceptable than a slightly cool one.

From their eight-hour-long experiments Berglund and Gonzalez [28] concluded that a temperature ramp of 0.6 K h^{-1} between 23 and 27°C was thermally acceptable to more than 80% of the subjects (wearing summer clothing). This would imply an increased comfort zone. The section on temperature drifts or ramps in the ASHRAE standard [7] states that "... *slow rates of operative temperature change (approximately* 0.6 *K/h) during the occupied period are acceptable provided the temperature during a drift or ramp does not extend beyond the comfort zone by more than* 0.6 *K and for longer than one hour.*" This statement is most probably based on these results. As indicated above, the results are however based on a different acceptability assessment from the usual ones. Furthermore, as Benzinger [13] points out, the results may have been influenced by the fact that man's thermoregulatory set point is higher in the afternoon than in the morning; that is, our tolerance for heat increases during the day. In view of this, the ASHRAE standard [7] should probably be restricted to acceptable changes during daytime and in upward direction only.

From Nevins' [24] experiments with cyclical changes with average fluctuation rates of 19 K h^{-1} it was concluded that there was no clear evidence of increased or decreased comfort zones due to fluctuation of ambient temperature. As pointed out by McIntyre and Griffiths [22], the results of the experiments with about the same average fluctuation rate by Wyon *et al.* [21] on the other hand do seem to provide evidence of decreased acceptable ranges due to fluctuation.

From experiments in the 1950s by Hensel (also reported in [11]) it became clear that when the human skin is exposed to changing temperatures the difference between neutral temperature and the temperature at which warm or cold sensations occur (i.e. thermal sensation threshold) decreases inversely with the rate at which the temperature is changed. This thermal sensation threshold depends also on the temperature to which the

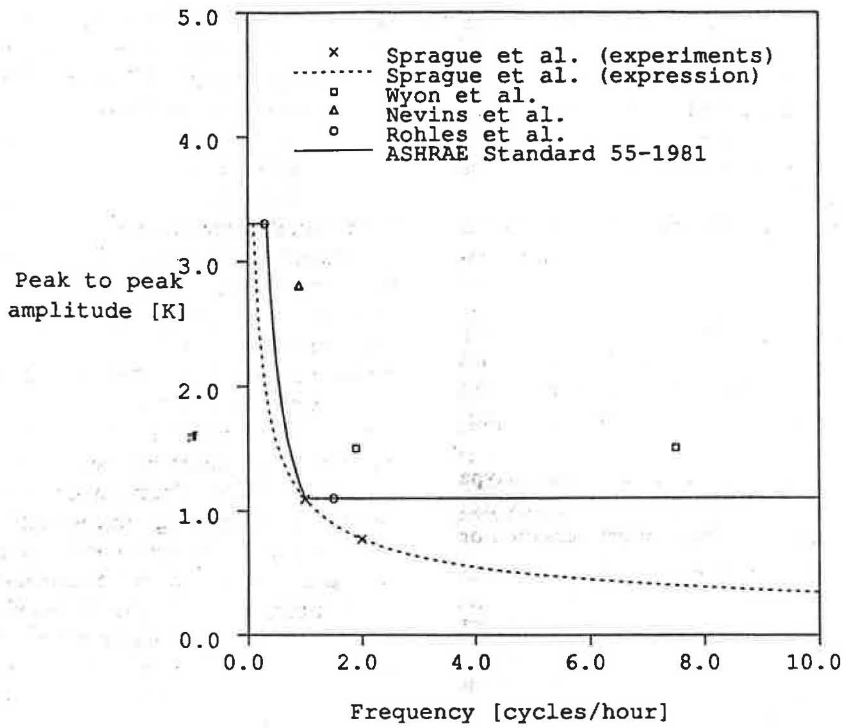

Fig. 2. Maximum acceptable peak-to-peak amplitudes of cyclical fluctuating operative temperature as a function of cycle frequency for near-sedentary activity while wearing summer clothing (derived from Sprague and McNall Jr [20],* Wyon [23],* Nevins *et al.* [24], Rohles *et al.* [26], ASHRAE [7]†).
* Operative temperatures estimated from given dry bulb temperatures (see text).
† Value at 0.0 cycles h^{-1} indicates width of steady-state comfort band.

skin is adapted when the change starts, on the direction of change, on the exposed part of the body and on the area being exposed. The latter two factors have a considerable influence on the intensity of temperature sensation as well. Although it cannot be proved, these aspects may very well be partly the cause of the contradictory results and conclusions of the experiments discussed above. The fact that there is a threshold for thermal sensations, and that this threshold is affected by the rate of temperature change, makes it likely that the same is true for thermal comfort. This would be in support of Fig. 2.

Contradictory results are also found with respect to sex differences. Wyon *et al.* [31], using high-school pupils, found significant differences between the responses of male and female subjects when exposed to changes in ambient temperature (about 4 K h^{-1}). Males in general feel hotter and react faster than females. Nevins *et al.* [24], using college age males and young and older female office workers, reported that the females had significantly higher warmth sensitivity than the male group.

An explanation for these and previously mentioned contradictions may be related to the choice of subjects (i.e. sampling error). This can be deduced from the conclusion of Stolwijk [32] who, after reviewing a considerable amount of research in this area, states: "*Differences in effectiveness of the thermoregulatory system in different individuals will result in different dynamic comfort responses to changing thermal environments: people with efficient thermoregulation will experience thermal discomfort sooner than those with less effective thermoregulatory systems. Our knowledge of the distribution of thermoregulatory efficiency among people is still very limited.*"

The effect of the level of clothing insulation and activity on man's thermal sensitivity during temperature changes was investigated by McIntyre and Gonzalez [33]. They exposed young college males who were either heavily clothed (1.1 clo) or almost nude and who were either resting (1.1 met) or bicycling (2.3 met) to a 6 K step change in air temperature. The temperatures were so chosen that the subjects started warmer than neutral and finished cooler than neutral. The experiments took place in June and where partly replicated in August (after summer heat acclimatization) to see whether there are seasonal changes in thermal sensitivity. From the results it was concluded that in general the change in whole body thermal sensation was affected by clothing, exercise and season. For resting subjects thermal sensitivity was not affected by clothing insulation or season. However the change in skin temperature following a change in air temperature was greater when unclothed than clothed. From this the authors concluded that change in mean skin temperature is therefore not an adequate predictor of thermal sensation. For unclothed subjects thermal sensitivity was greater when resting than when exercising. The responses of clothed, exercising subjects interacted with season (e.g. they felt cooler in August).

As indicated earlier, the effect of greater sensitivity during rest than when performing mental work was also found with the cyclical temperature change experiments by Wyon *et al.* [21]. That clothing insulation does not seem to have an effect on thermal sensitivity may be explained by the fact that in general various thermally sensitive parts of the body (e.g. hand, neck, hands) are uncovered.

Probably because of the minor influence of moderate humidities on thermal comfort and thermal sensation, there are only few experiments reported which investigate the effect of changing humidity. Four studies, those by Gonzalez and Gagge [34], Nevins *et al.* [24], Gonzalez and Berglund [35] and Stolwijk [32] all indicate that when operative temperature is inside or near the comfort zone, fluctuations in relative humidity from 20 to 60% do not have an appreciable effect on the thermal comfort of sedentary or slightly active, normally clothed persons. Relative humidity becomes more important when conditions become warmer and thermoregulation depends more on evaporative heat loss.

Regarding changing air velocities no references have been found except of course those dealing with the effect of air turbulence on sensation of draught. Velocity fluctuations due to turbulence are in general much faster (ranging from 0.01 to 10 Hz) than ambient temperature fluctuations which generally can be measured in units of cycles h^{-1}. Fanger *et al.* [36] concluded that an air flow with high turbulence causes more complaints of draught than air flow with low turbulence at the same mean velocity. As possible reasons for this were mentioned the relation between convective heat transfer and turbulence and the relation between the heat flux (or rate of temperature change) as sensed by the skin thermoreceptors and turbulence.

Finally it is repeated that care must be taken in applying the above results. In general many contradictory results have been found. These were most pronounced with respect to rate of temperature change, sex difference and age difference. The possible reasons are already indicated in the previous sub-section.

4. CONCLUSIONS

Our theoretical knowledge concerning thermal comfort in transient conditions is still limited. At present, results of thermal comfort experiments seem to be the only source of information on thermal acceptability in changing environmental conditions.

The present study is restricted to conditions characteristic for homes, offices, etc. The following conclusions are supplementary to the steady-state comfort criteria which are usually associated with those conditions; i.e. sedentary or slightly active persons, wearing normal indoor clothing in an environment with low air movement (<0.15 m s^{-1}) at 50% relative humidity.

The experimental results related to *cyclical* fluctuating ambient temperatures are, although perhaps a little conservative, quite adequately described by ASHRAE's standard [7] which states with regard to cyclic changes: "*If the peak variation in operative temperature exceeds* 1.1 *K the rate of temperature change shall not exceed* 2.2 *K/h. There are no restrictions on the rate of temperature change if the peak-to-peak is* 1.1 *K or less.*"

With respect to temperature *drifts* or *ramps*, there is good experimental evidence that at rates of operative temperature change below 0.5 K h^{-1}, the environment is experienced as in steady-state conditions. At rates between 0.5 K h^{-1} and 1.5 K h^{-1} there is, apart from experiments with uncommon acceptability assessment procedures, no clear evidence of increased or decreased comfort zones due to transient conditions. The paragraph in ASHRAE's standard [7] states that "... *slow rates of operative temperature change (approximately* 0.6 *K/h) during the occupied period are acceptable provided the temperature during a drift or ramp does not extend beyond the comfort zone by more than* 0.6 *K and for longer than one hour*", but this should probably be restricted to acceptable changes during daytime and in an upward direction only. No evidence was found why the limit for cyclical changes (i.e. if the rate of temperature change exceeds 2.2 K h^{-1} the peak variation shall not exceed 1.1 K) would not be valid for temperature drifts and ramps as well as for higher rates of change of operative temperature.

From several experiments it was found that *clothing insulation* has a negligible effect on thermal sensitivity during temperature changes. This implies that the limits stated above are valid for summer as well as winter conditions.

Regarding *activity level*, a greater sensitivity was generally found during rest than when performing mental work. From this it follows that the above limits may be regarded as conservative in case of light sedentary activity in offices, homes, etc.

Provided operative temperature is inside the comfort zone, *humidity* fluctuations, when relative humidity is in the range from 20 to 70%, do not seem to have an appreciable effect. Regarding changing *air velocity*, no references were found except those dealing with the effect of increased draught complaints when air turbulence is higher.

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