

Thermal Comfort During Exposure to Drifting Operative Temperatures

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INTRODUCTION

The fact that about one third of the primary energy production in developed countries is consumed by heating, ventilating and air conditioning of non-industrial and residential buildings initiated extensive development of new HVAC systems that allow indoor climate control with reduced energy demand. Some of these systems are associated with moderate drifts of indoor temperatures, also during the building occupancy period. Allowing indoor temperatures to drift rather than to keep them steady, which is common practice in most air-conditioned buildings, may be a feasible means to reduce the building energy demand. The results of previous research suggest that slow temperature ramps up to ± 0.5 K/h (23-27°C) have no influence on the width of the comfort zone as established under steady-state conditions [1, 2]. Berglund and Gonzalez [1] also concluded that temperature limits for 80% acceptability of the thermal environment, particularly the upper limit, defined by ASHRAE Standard 55 [3] might be conservative in case of drifting temperatures. Knudsen et al. [4] addressed the possibility to use the PMV/PPD model [5] to predict thermal sensation during temperature ramps up to ± 5 K/h. Although previous studies conducted in the climate chambers examined a large range of temperature ramps, their focus was mostly on establishing temperature limits for acceptable thermal comfort. The objective of this project was to extend the knowledge on the effect of moderate operative temperature drifts to cover not only on human thermal comfort, but also on the intensity of SBS symptoms and perceived air quality.

METHODS

Fifty two healthy subjects (mean age: 23.7 ± 4.4 [yrs]; mean height: 176.6 ± 9.4 [cm]; mean weight: 74.7 ± 11.9 [kg]; 50% female), recruited college students, were seated in a climatic chamber and exposed to different conditions during two related experimental series; see Table 1. The climate chamber (5 m wide, 6 m long and 2.5 m high) was developed to control accurately the thermal environment [6]. Ventilation system provided approx. 170 L/s of fresh air (air change rate 9 h^{-1}). That corresponds to about 28 L/s per person when considering 6 persons seated in the chamber at the time. Air and operative temperatures, which were identical during all exposures, air velocity and air humidity was measured continuously at the centre of the chamber at 0.6 m above the floor. The water vapour pressure 1.53 kPa (corresponding to 50% RH at 24°C) was kept constant during all exposures.

In both experimental series, subjects were divided into groups of six. Each group came to an experimental session on the same week-day. Each group experienced one condition a week. The order of the conditions was randomized (Latin Square Design). Subjects were seated at separate

workstations consisting of a desk, a chair and a PC. Each session started with an acclimatization period (30 min.). Two times per hour, subjects filled in a questionnaire that included a 7-point thermal sensation interval scale, scales to assess the acceptability of the thermal environment and perceived air quality, a scale to assess odour intensity (Figure 1a) and Visual Analogue Scales (VAS) to assess the intensity of selected specific and general SBS symptoms [7]. A scale to assess self-estimated performance was also included in the questionnaire. Subjects' performance was measured by simulated office work tasks but these results are not included in this paper. Both questionnaires and office work tasks were presented to subjects in an Internet browser [8]. Subjects wore their own clothing during all experimental sessions. Clothing composition was determined during pre-sessions in which subjects were exposed to constant operative temperature 24.4 and 21.4°C (50% RH, 2 hours) for experiment 1 and 2 respectively. They were also allowed to move around the chamber casually, so that their metabolic rate was approximately 1.2 met.

The percentage of subjects dissatisfied with their thermal condition was determined by calculating the percentage of votes that were placed in "negative" part of the thermal acceptability scale (from "just unacceptable" to "clearly unacceptable") for each vote.

RESULTS

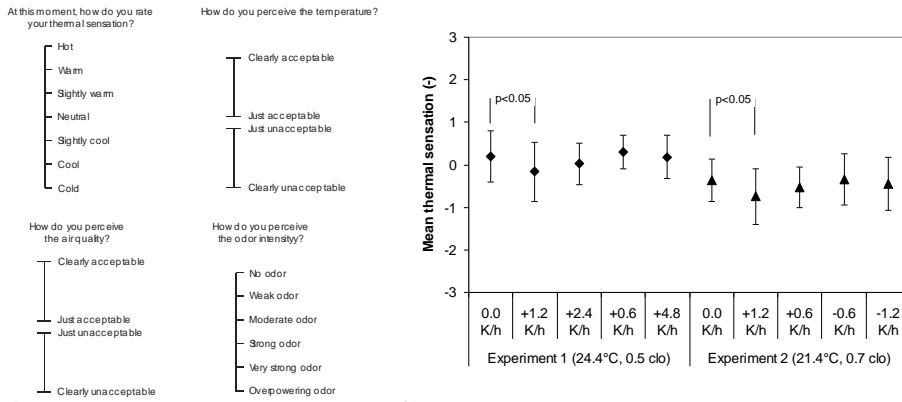
Results of the thermal sensation and acceptability are presented.

Thermal sensation

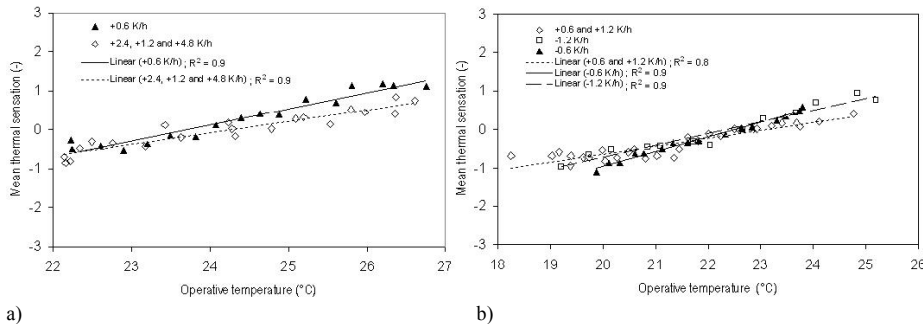
Comparison of the mean thermal sensation from conditions with constant temperature (24.4 and 21.4°C) to data from the same temperature level reached by ramps is depicted in Figure 1b. The analysis showed, that mean thermal sensations differed significantly only in case of comparison to +1.2 K/h ramp at both temperature levels.

Linear relation between thermal sensation and operative temperature was observed in all studied ramps. The data obtained in experiment 1 are depicted in Figure 2a. Analysis with Linear Mixed Effects model showed that an intercept and slope of the linear relation did not differ significantly for +2.4, +1.2 and +4.8 K/h ramps. For these ramps, subjects perceived operative temperature the same way regardless the ramp they were exposed to. Common linear fit for +2.4, +1.2 and +4.8 K/h ramp is indicated by dash line in Figure 2a. The development of thermal sensation was different in +0.6 K/h ramp (Figure 2a – solid line), where thermal sensation for the same level of operative temperature was higher. This difference tended to be larger for higher temperatures. Analysis showed significant difference in both slope and intercept ($p < 0.001$) when +0.6 K/h ramp was compared to +2.4, +1.2 and +4.8 K/h ramps.

Figure 2b presents linear relation between operative temperature and mean thermal sensation in experiment 2. Analysis of the data showed no significant difference in both slope and intercept of the regression line for +0.6 and +1.2 K/h ramp. Common linear fit for +0.6 and +1.2 K/h ramp is indicated by dash line. In case of decreasing ramps, the thermal sensation changed with temperature significantly faster than in increasing ramps. Solid line in Figure 2b represents linear fit for -0.6 K/h ramp data. Its slope is significantly different ($p < 0.0001$) from the one of the line representing increasing ramps (+0.6 and +1.2 K/h). The slope of -1.2 K/h ramp differed both from the slope of increasing ramps ($p < 0.05$) and the slope -0.6 K/h ramp ($p < 0.01$).



a) Interval and acceptability scales; b) Comparison of mean thermal sensation at the level of thermal neutrality reached by temperature ramps to data from exposure to constant temperature, vertical bars indicate \pm SD



a) Mean thermal sensation votes as a function of operative temperature: a) experiment 1 - 22-26.8°C, 0.5 clo, b) experiment 2 - 17.8-25°C, 0.7 clo.

Acceptability of air quality and intensity of odour

The results from exposures to constant temperature indicated that subjects needed approximately 120-150 minutes to adapt their olfactory senses to the pollution level in the climatic chamber. During exposure to temperature ramps, acceptability of air quality was linearly dependent on operative temperature. This relationship was statistically significant for +0.6 K/h ramp in experiment 1 and -1.2 K/h ramp in experiment 2 (Figure 3). The results seem to be in agreement with results obtained by Fang et al. [9]. The effect of adaptation observed in steady state conditions couldn't be studied in case of temperature ramps as acceptability of air quality was affected both by changing temperature (enthalpy) and different initial temperature level. No significant change in intensity of odour was observed in experiment 1 and 2. Overall means were

0.8 ± 0.6 and 0.7 ± 0.5 for experiment 1 and experiment 2 respectively, which corresponds to a little bit less than “slight odour” category on the scale.

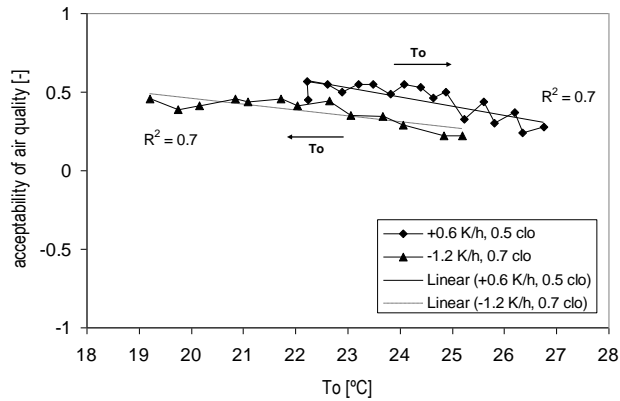


Figure 3. Acceptability of air quality as function of operative temperature; arrows indicate direction of the temperature ramp

DISCUSSION

Subjects dressed in summer clothing (approx. 0.5 clo) immediately perceived operative temperature ramps +2.4 K/h, +1.2 K/h and +4.8 K/h in range 22-26.8°C. The perception of thermal environment was the same regardless the experienced ramp. Temperature ramp +0.6 K/h was recognized with about 3 hours delay. Afterwards, the same operative temperature was perceived as warmer, than in case of steeper ramps. However, higher thermal sensation was not accompanied with higher dissatisfaction with the environment. During exposure to +0.6 K/h ramp at lower temperatures (19-23.8°C, 0.7 clo) subjects did not perceive given operative temperature differently from +1.2 K/h ramp. This results suggest that not temperature ramp itself, but rather combination of temperature level above 24.4°C and time of the exposure influenced thermal sensation of the subjects. Although the design of the experiment did not allowed to separate the effect of rising temperature and the time effect, the fact that subjects spent 8 hours in the climatic chamber could bring on fatigue that consequently influenced the thermal sensation. The results of the present study seem not to be in conflict with findings of the previous research [1]. Subjects did not distinguish slow temperature increase +0.6 K/h for the first 3 to 4 hours of the exposure. However, as the exposure continued, linear relation between thermal sensation and temperature was observed. Higher level of clothing insulation seemed to enlarge the delay period for flat ramps (+0.6 K/h) and even introduce it for steeper ramps (+1.2 K/h).

Comparison of the percentage dissatisfied with thermal environment obtained in the present study to the prediction by PMV/PPD model did not consistently show that acceptability range specified by current standards [3, 5] could be extended when subjects were exposed to temperature ramps. In +4.8K/h ramp percentage of dissatisfied increased faster than predicted by

the model. On the other hand, subjects accepted slightly warm environment during +0.6 K/h ramp more than the model would predict. The data from ± 1.2 , +2.4 and -0.6 K/h ramps followed quite well relationship given by PMV/PPD model. Rather high percentage of dissatisfied in exposure to constant temperature 24.4°C can not be fully explained. It is possible that as thermal acceptability data were not adjusted for higher initial metabolic rate, higher dissatisfaction in the beginning of the ramp influenced the mean value.

Observed relationship between acceptability of air quality and operative temperature (respective enthalpy of the air) suggests that in case of insufficient ventilation, temperature increase can cause further degradation of perceived air quality. Poor air quality may, in the end, result in increased intensity of SBS symptoms, decrease overall comfort and productivity of the occupants.

CONCLUSIONS

- | ☐ Linear relationship between mean thermal sensation and operative temperature was observed in all studied ramps. Flat ramps (± 0.6 K/h) were realized by sedentary subjects with 3 to 4 hours delay (depending on the level of clothing).
- | ☐ Relationship between mean thermal sensation and percentage of thermally dissatisfied subjects was in fairly good agreement with prediction by PMV/PPD model. In general the results do not indicate that it would be possible to extend the comfort zone specified in current standards.
- | ☐ Adaptation to indoor air quality occurred after approx. 2 hours in exposure to steady temperature. Linear relationship between acceptability of air quality and temperature (enthalpy) was observed in temperature ramps.
- | ☐ Increasing operative temperature had a slight but significant negative effect on general SBS symptoms like intensity of headache, well feeling or fatigue. The same stands also for self evaluated concentration ability and performance.

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