Assessment of Adaptive Thermal Algorithm in Office Buildings

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ABSTRACT

Being the largest energy consumer, building sector represents a major stake for the actual environmental concerns. So far, building thermal comfort standards are based on static models that don't account for the interaction between occupants and their living places. The adaptive approach of the thermal comfort has the advantage to be more comprehensive and realistic, and its application would result in energy saving in buildings. Recently, an Adaptive Control Algorithm ACA and an Adaptive Comfort Standard ACS have been developed on the adaptive approach. We propose in this study to assess the adaptive algorithms ACA and ACS through a field study that has been carried in four naturally ventilated and three climatically controlled office buildings located in France during summer and winter conditions. In the paper, we present a description of the experimental method and the buildings followed by the description of indoor environments. The neutral temperatures are determined, for various seasons in both types of buildings. The results are analysed and then compared to the requirements of current thermal standards showing their limits. Finally, the adaptive algorithms are assessed showing its validation in the case studies.

KEYWORDS

Thermal comfort, Adaptive models, Field experiment, office buildings

INTRODUCTION

Actual standard of thermal comfort in buildings are based on static models that don't account for the complexity of comfort and the interaction between occupants and their living places at work or at home. These standards are acceptable for air conditioned (AC) buildings, but they are unreliable for the case of naturally ventilated (NV) buildings. Field studies conducted in both type of buildings have shown that occupants of NV buildings accept and prefer a significantly wider range of temperatures compared to occupants of AC buildings (Brager et al, 2004). The results of these field studies have contributed to develop the adaptive approach of thermal comfort in buildings. This approach focuses on the ability of people to adapt to their thermal environments in NV buildings that afford them greater degrees of control over thermal conditions. Such an approach has the advantage to be more comprehensive and realistic. It allows more variable indoor temperatures that cycle or drift in response to the natural swings of the outdoor and indoor climate. Its application would result in energy saving in buildings.

Recently, an Adaptive Control Algorithm (ACA) and an Adaptive Comfort Standard (ACS) have been developed on the adaptive approach. These algorithms need to be evaluated across different types of buildings to encourage their use. This paper presents a field study that was conducted in NV and AC office buildings in order to explore the indoor thermal climate and to compare it to the requirements of actual standards. This study will also enable us to assess the adaptive algorithms ACA and ACS.

METHODOLOGY

Data collection procedures

The study was conducted in four NV office buildings during August 2004 and March 2005. Besides, three AC office buildings were studied on the period from May to June 2005. Buildings are located in the south east region of France. The NV office buildings are typically low rise buildings with a heavy concrete structure, large glazed facades and operable windows. They are heated during winter and free running during summer. Occupants are free to open their windows or make use of the blinds. The majority has a local fan in their offices. The AC office buildings are high rise buildings with highly glazed facades and no operable windows and they are centrally controlled, except one where occupants can open windows and have a personal control through a remote control.

Each building was visited five times during a week on the period of measurement. At each visit, ten to fifteen subjects were inquired during fifteen minutes. Participants had to complete a thermal assessment questionnaire addressing thermal sensation, thermal acceptability, thermal preference, comfort, activity, clothing and the use of different thermal environment control means. At the same time and place, all indoor physical environmental variables were measured using a full set of transportable instruments. A total of 120 subjects have participated in the study making a total of 400 contributions.

The detailed descriptions of the data collection methods, surveys, and instrumentation are presented by Moujalled et al (2005).

Data processing

The collected questionnaires data were numerically coded and merged with physical measurements data in a single excel work sheet. This enabled us to calculate the standard comfort indices. First we have calculated the PMV and PPD indices according to the Standard ISO 7730 (2003). Then we have calculated the Effective Temperature ET* and Standard Effective Temperature SET indices indicated by the ASHRAE (1997) using the two node model of Gagge (Gagge, 1986).

Along with standard comfort indices, we have calculated comfort temperature T_C from ACA algorithm (McCartney et al, 2002) and the ACS standard (De Dear et al, 2002). Equations 1 to 3 show the algorithm used to find T_C. For the ACA, we have used the equations given for France.

$$T_c=0.049T_{MR80}+22.58 \quad \text{for } T_{MR80}\leq 10°C \text{ (ACA)} \qquad \text{Eqn. 1}$$

$$T_c=0.206T_{MR80}+21.42 \quad \text{for } T_{MR80}>10°C \text{ (ACA)} \qquad \text{Eqn. 2}$$

$$T_C = 0.31 T_{a,o} + 17.8 \text{ (ACS)} \qquad \text{Eqn. 3}$$

The running mean outdoor temperature T_{MR80} was calculated on each day from the weather data file of a weather station located on one of the studied buildings and that presents similar outdoor conditions as for the other buildings. By the same way the mean outdoor dry bulb temperature $T_{a,o}$ was found. To define a comfort zone band around comfort temperature T_C, we have considered for the ACA an upper comfort temperature limit dT_C corresponding to 90% acceptability as defined by El Mankibi (2003) in Eqn. 4.

$$dT_C = -0.19 T_C + 6.34 \text{ (ACA)} \qquad \text{Eqn. 4}$$

For the ACS we have used a mean comfort zone band of 5°C for 90% acceptability and 7°C for 80% acceptability (de Dear, 2002).

RESULTS

Basic summaries

Figure 1 shows the frequency distribution of the operative temperature in NV buildings during summer and winter measurements and in AC buildings. The indoor operative temperature has widely varied in the VN buildings during summer conditions with a mean of 27.7°C and a standard deviation of 2.7°C. During winter variations were narrower and temperatures have averaged around 24°C.

In AC buildings the temperature rise was limited during hot period. The distribution of the operative temperature in these buildings (curve with box marker on figure 1) presents three peaks which correspond to each of three monitored AC buildings with the lowest peak happening in the building that offers personal control to occupants. We can notice that occupants allow higher temperatures when they have control over thermal conditions.

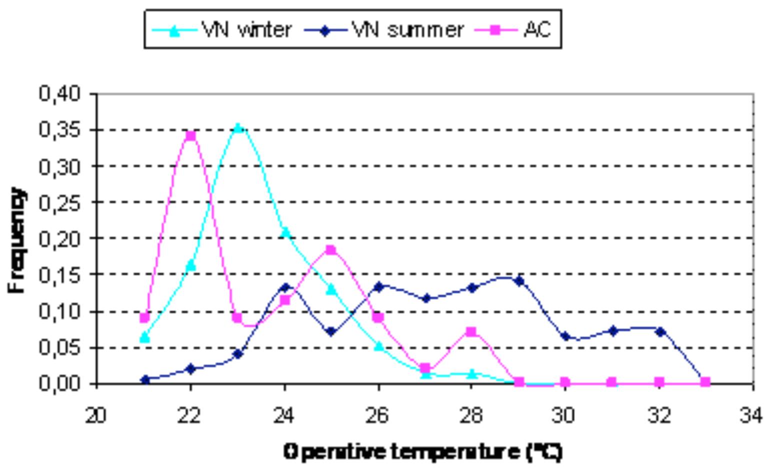

Figure 1 : Frequency distribution of the operative temperature

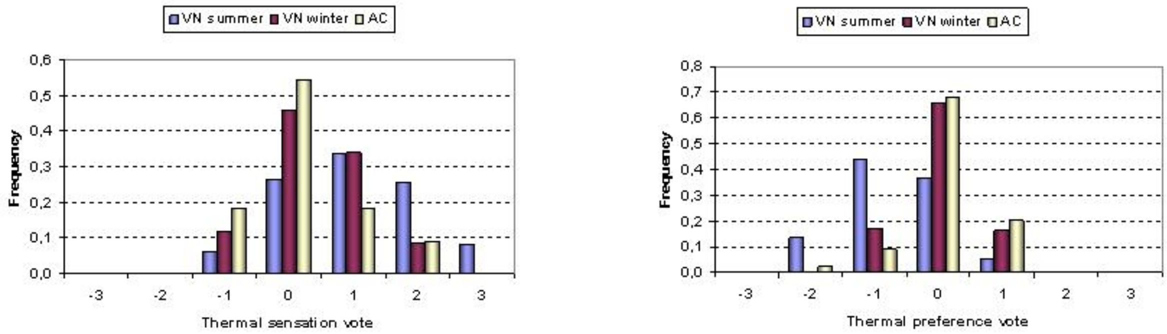

Figure 2 : Frequency of distribution of thermal sensation and preference votes

The first graph in figure 2 at left shows the distribution of the thermal sensation votes. For the case of NV buildings during summer, the mean sensation vote was on the warm side of neutral with a mean equal to +1. During winter conditions it was closer to neutral sensation being slightly larger than zero (+0.4). In AC buildings, thermal sensation was neutral on average. The second graph at right on figure 2 shows the distribution of thermal preference votes. As expected, people in NV buildings preferred on average to be cooler but the distribution wasn't symmetrical to sensation vote's distribution. People do not prefer in fact to be cooler by the same amount when they feel warm or hot. We notice also some percentage of people who want to be cooler in winter conditions. This means that NV buildings are overheated in winter.

Comparison with comfort standards

Physical measurements and comfort votes have been compared to the requirements of ISO 7730 standard and ACA and ACS comfort range. The results are shown in table 1. In the first line we present the percentage of votes that had the predicted PPD lower than 10%. In the following three lines are presented the percentages of votes having the measured operative temperature within the comfort zone of ACA and ACS and in the last line the percentage of people who were voting comfortable.

For the case of NV buildings, the best agreement with measurements was obtained with the ACA that had the percentages (52% in summer and 79% in winter) fairly close to the measured ones either in summer (48%) or winter (83%). For the ACS, only applicable in summer conditions, the measured percentage was in between the percentages obtained for 80% and 90% acceptability. The worst result happened with the standard PPD (31% in summer and 67% in winter) who was overestimating measured discomfort in both summer and winter conditions.

In the AC buildings, the percentage of people voting comfortable (77%) was closest to the results of the ACS (82%). The ACA (93%) was underestimating it by 16%. Once again the PPD has overestimated the percentage of discomfort but not as much as in the case of NV buildings. If the adaptive algorithms were more successful in predicting comfort in NV buildings than in AC buildings, this could be explained by the relaxation of expectations and greater tolerance of temperature excursion of the occupants in NV buildings as suggested by the adaptive approach of thermal comfort (Brager et al, 2004). People in AC buildings are becoming demanding and have low tolerance to any change in their conditions since they don't have control over it.

TABLE 1
Comparison of comfort vote with standards

	NV (winter)	NV (summer)	AC
% of votes with predicted PPD <10%	67%	31%	66%
% of votes respecting ACA 90% acceptability	79%	52%	93%
% of votes respecting ACS 90% acceptability	-	41%	82%
% of votes respecting ACS 80% acceptability	-	60%	93%
% of subjects voting comfortable	**83%**	**48%**	**77%**

Neutral temperature vs. adaptive standards

We have examined the relationship between thermal sensation and the physical thermal environment by calculating the linear regressions between thermal sensation votes and the binned operative temperatures weighted by the number of observations in each bin. The thermal sensation was highly correlated to the indoor temperature in NV buildings during summer (r^2=0.86) and winter (r^2=0.85). The fitted linear curves had a slope of 0.23/°C for the NV buildings in summer and 0.30/°C for the same buildings in winter. This means that occupants of NV buildings were less sensible to change in indoor temperature in summer than in winter. For the AC buildings, the data failed to achieve a statistical significant relationship unfortunately. This could be explained by the small number of temperature bins that happened in these buildings.

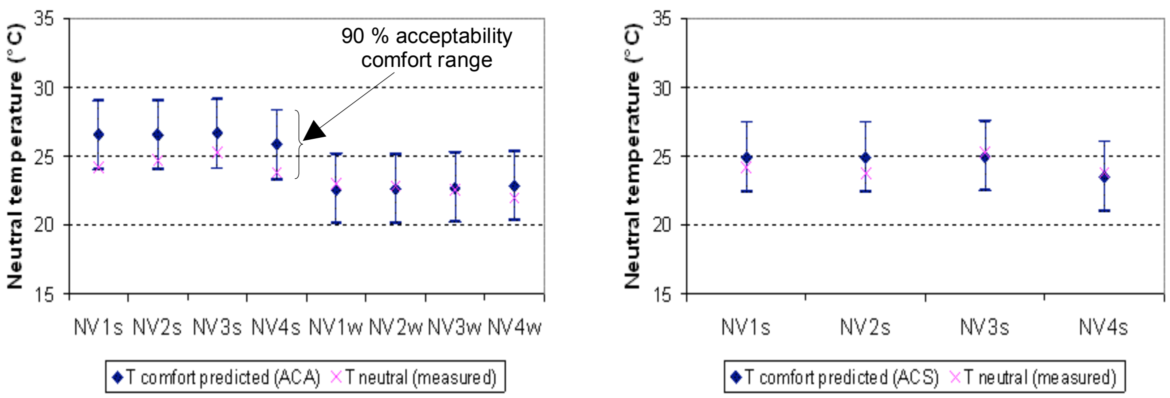

Figure 3 : Measured neutral temperatures compared to the adaptive model's predicted comfort zone in each of studied NV buildings in summer (subscript s) and winter (subscript w).

The equations can be used to find the neutral operative temperature which is considered traditionally as the ideal comfort temperature (Brager, 2004). It is determined by solving the regression equations for thermal sensation equal to zero. We present in figure 3 the measured neutral temperatures in the four studied NV buildings for summer and winter conditions along with the predicted comfort temperature T_C from the adaptive models ACA (on the left panel) and ACS (on the right panel). The comfort temperatures are considered with the 90% acceptability comfort zone. In general, neutral temperatures fall within the comfort ranges of ACA and ACS model but they are closer to the ACS optimum comfort temperature.

CONCLUSIONS

In this study we have investigated the thermal conditions in four NV buildings during hot and cold season along with three AC buildings during hot season. From this study we can draw the following conclusions:

- Indoor thermal climate was in general warm in NV buildings during summer and more than the half of subjects were dissatisfied. The conditions were better in winter with the mean sensation being close to neutral. The AC buildings were doing better in the hotter period with a mean sensation slightly neutral.
- Subjects allow higher temperatures in AC buildings when they have control over their ambient conditions.
- The PMV and PPD indices are poor in predicting thermal comfort in NV buildings during summer and winter conditions. The PPD had overestimated the percentage of discomfort in both cases. The same tendency was found in AC buildings, the discrepancy being less severe.
- Both adaptive models (ACA & ACS) were successful in predicting thermal comfort in NV buildings. The percentages of indoor temperature falling within comfort range were very close to the measured discomfort. In AC buildings, they were less successful. One explanation to this could be the higher degree of expectations of people inside these buildings.
- Thermal sensation vote correlate very well with operative temperature in NV buildings, and people are less sensitive to temperature changes in these buildings in summer than in winter. The measured neutralities fall in general within the comfort ranges of the adaptive models (ACS and ACA).
- Finally, this study has shown the importance of the adaptive models in building design. Unlike the static approach (current standards) which tends to encourage the use of air conditioning systems, the adaptive approach allow the comfort conditions of the indoor climate to vary in wider ranges as in NV buildings. The possible gains are not only occupant comfort but also the use of energy.

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