Adaptive thermal comfort evaluation in a field study

B. Moujalled, R. Cantin and G. Guarracino
ENTPE-DGCB-LASH, rue Maurice Audin – 69518 Vaulx-en-Velin cedex, France

ABSTRACT

A field study of environmental conditions and occupant comfort were carried in four office buildings in the southeast region of France. The study was made during the summer and autumn seasons, collecting a full set of physical measurements and subjective responses. The measured environmental parameters are: air temperature, operative temperature, air velocity, relative humidity, CO_2 concentration, sound and light levels. The subjective responses concern the judgments of participants about the thermal environment at the moment of measurements.

In the paper, we describe first the protocol of measurements followed by the description of buildings environments along with the distribution of thermal sensation responses, neutral and preferred temperature and conditions of thermal acceptability. The conformity of the thermal environments to the requirements of thermal standards (PMV, SET) is then checked. The evaluation of the adaptive control algorithm is presented showing its utility.

1. INTRODUCTION

Actual thermal comfort standards are based upon laboratory studies carried in climatic chambers ignoring the complex interaction between occupants and their environment that could affect their comfort. Despite the agreement with results of field studies in climatically controlled buildings, occupants in free running buildings were found to be comfortable in wider range of conditions. With the increased interest to reduce energy -consumption in buildings, this complex Interaction should be considered for sustainable buildings. Recently, the European SCATs project has developed an Adaptive Control Algorithm (ACA) to control building temperature set point taking advantage of the adaptive approach to thermal comfort.

The objectives here are to explore the indoor thermal climate in naturally ventilated (NV) office building in the southeast region of France, and compare it to the requirements of the actual thermal comfort standards. The collected data will also be used to evaluate the adaptive control algorithm, and to look at the use of the means of control of the indoor thermal climate.

2. METHODOLOGY

The study was conducted from mid august 2004 till mid September 2004. In order to cover a large number of buildings, the transversal survey type (Humphreys and Nicol, 1998) was adopted with multiple visits to each building to obtain a wide interval of indoor conditions.

The field investigation was realized according to the level II (de Dear, 1998) respecting the specifications set out in the ISO standard 7726 (ISO 7726). All indoor physical environmental variables necessary for the calculation of thermal comfort indices (ISO 7730) were collected at the same time and place as comfort questionnaires were administered.

Hereafter, we present the buildings used in the study, the profile of the participants, the physical measurements, the questionnaires and the procedures of collecting data.

2.1 Buildings

Four office buildings were selected in the southeast region of France to conduct the survey. They are located in the same climatic zone: west coast marine. All of the four buildings are naturally ventilated (NV), and were chosen on the basis of occupants' willingness to participate, the building characteristics (interior layout, age, structure) and expected interior thermal conditions.

The buildings will be referred as A1, A2, B and C in what follow. They have almost the same structure: low rise, heavy concrete and large glazed facades. Buildings A1 and B are equipped with interior Venetian blind, A2 and C with interior textile curtain blind. Only building C has an open layout.

2.2 Participants

A total of 50 subjects have participated in the study making a total of 184 contributions. The responses were composed of 90 males (49 %) and 94 females (51 %). The ages in the sample range from 18 to 59 years and have a mean of 37. Figure 1 shows the frequency of participation of subjects by building.

2.3 Physical measurements

Figure 2 shows the instruments used in field to make the measurements. The physical thermal environment variables were measured using the Vivo instruments. The indoor CO_2 concentration, the light level and the sound level were also measured. On Figure 2, we can distinguish unit V1 for air temperature and air velocity measurements, V2 for the operative temperature, V3 for air relative humidity, C for CO_2 concentration, L for light level and S for sound level measurements.

Temperature data loggers were lifted in the office of each participant, and have registered the air temperature during the building monitoring duration at a time step of five minutes.

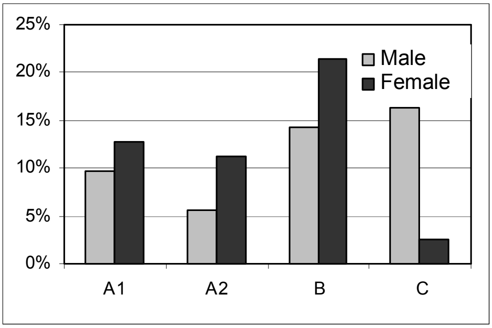

Figure 1: Frequency of participation by building.

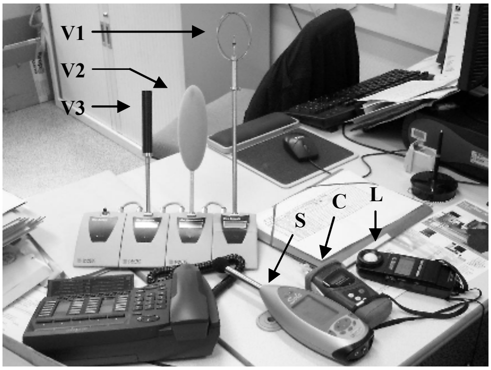

Figure 2: The indoor measurements instruments.

Outdoor climate conditions were obtained from the ENTPE weather station. It is located on building A1 which has similar outdoor conditions as for the other buildings. The station supplies the instantaneous values of dry bulb air temperature, relative humidity, wind speed and direction each five minute.

2.4 Questionnaires

The questionnaire consisted of four different sections. The first section asks the subjects to evaluate their thermal environment at the moment of measurements according to the standard ISO 10551 (ISO, 2003).

The second section is the clothing and activity checklists. We developed separated clothing checklists for male and female on the basis of the ISO 9920 (ISO, 2003). The activity checklist inquired about physical activity, eating, drinking (hot or cold) and smoking during the hour previous to taking the survey.

In the third section, we ask the subject to evaluate the interior air quality, the lighting and the sound quality, and the overall quality of the indoor environment at the moment of measurements on a 7 points scale, to finish with the fourth section by a checklist on the use of different thermal environment control means (windows, local fan, shading device).

2.5 Data collection procedures

All buildings were visited 5 times during a week on working days. Visits last half day each, and were alternated between the morning and the after noon, and take ten minutes per each participant.

The protocol for each work station visit was as follows: we approach the subject and present the comfort survey if convenient; meanwhile we put the Vivo on the desk of subject and set it for a 10 minutes measurement sequence with a 30 seconds time step. We take the instantaneous values of CO_2 concentration, the light level and the sound level.

2.6 Data processing

Questionnaire data were numerically coded and transferred to an excel file to facilitate statistical analysis. Clothing thermal insulation values were determined, for each subject, from the individual clothing articles indicated in the survey responses with respect to the ISO 9920 (ISO, 2003). Metabolic rates values were also determined from the activity checklist inquired by subjects.

Collected physical measurements were entered in an excel file, and both, the physical measurements and questionnaire data, were merged on a single excel work sheet. From this database, we have calculated different thermal comfort indices as explained below.

2.7 Rational comfort indices

A matlab program was developed, using the method specified in the standard ISO 7730 (ISO, 2003), to calculate the PMV and PPD indices.

Another program was adapted from the Gagge model (Gagge et al., 1986) and was used for calculating environmental indices such as ET* and SET and comfort indices such as TSENS and DISC (ASHRAE, 1997).

2.8 Adaptive comfort indices

To calculate the adaptive control algorithm (ACA) comfort temperature in naturally ventilated buildings, we have used the algorithm given by McCartney and Nicol (2002) for France:

$$Tc = 0.049T_{MR80} + 22.58 \text{ for } T_{RM80} \leq 10\ °C$$

$$T_C = 0.206T_{MR80} + 21.42 \text{ for } T_{MR80} > 10\ °C$$

$$T_{RM80} = 0.80T_{RMn-1} + T_{DMn-1}$$

where:

Tc: Indoor comfort temperature (°C)

T_{RM80}: Running mean outdoor temperature for index 0.80 (°C)

T_{RMn-1}: Running mean outdoor temperature on day n-1 (°C)

T_{DMn-1}: Daily mean outdoor temperature on day n-1 (°C)

T_{RM80} was calculated on each day from the weather data file. To define a range of temperature around T_C corresponding to 90 % acceptability, we have used the following formula developed by El Mankibi (2003):

$$dT_C = -0{,}19T_C + 6{,}34$$

where:

dT_C: upper comfort temperature limit corresponding to 90% acceptability (°C)

Another attempt was made to estimate the comfort temperature using the adaptive control standard (ACS) developed by de Dear and Bragger (2002). We have calculated the optimum comfort temperature Tc in NV buildings given by the following formula:

$$Tc = 0.31Ta{,}o + 17.8$$

where:

Tc: Indoor comfort temperature (°C)

Ta,o: Mean outdoor dry bulb temperature (°C)

Ta,o has been calculated from the weather file for each day of the monitoring duration. The mean comfort zone band is 5°C for 90 % acceptability, and 7°C for 80 % acceptability.

3. RESULTS

3.1 Basic summaries

Table 1 provides statistical summaries of the measured thermal physical data in the four buildings, and Table 2 compares these results with the ISO comfort standard (ISO, 2003) and the ASHRAE summer comfort standard (Schiller et al., 1988).

For all four buildings, the indoor operative temperature ranged between 21,9°C and 32,9°C with a mean of 27,4°C. Overall, 68,9% of the operative temperature measurements were outside the standard comfort zone limit, except for building B (30%) where the measurements have been made during the second week of september.

The air velocity is relatively higher in buildings A1, A2 and C than in B. This is due to the fact that almost all of the participants in these

Table 1: Distribution of Physical Data – Summer 2004.

Building	A1	A2	B	C	All
Sample size	44	33	70	37	184
Air temp °C					
mean	27,9	29,6	24,9	29,8	27,4
standard deviation	1,9	1,1	1,6	2,9	2,8
minimum	23,7	26,9	21,9	23,2	21,9
maximum	32,4	32,3	28,7	32,9	32,9
Operative temp °C					
mean	28,3	29,8	25,1	29,8	27,6
standard deviation	1,8	1,2	1,6	2,7	2,7
minimum	24,6	26,7	21,7	23,5	21,7
maximum	32,5	32,6	28,7	32,7	32,7
Air velocity m/s					
mean	0,2	0,2	0,1	0,2	0,2
standard deviation	0,2	0,1	0,1	0,1	0,1
minimum	0,0	0,0	0,0	0,1	0,0
maximum	0,5	0,4	0,3	0,6	0,6
CO_2 concentration ppm					
mean	784	875	706	998	831
standard deviation	173	268	157	284	258
minimum	580	530	110	740	110
maximum	1200	1100	1090	1200	1200
Clothing clo					
mean	0,5	0,5	0,6	0,5	0,5
standard deviation	0,1	0,1	0,1	0,1	0,1
minimum	0,4	0,4	0,4	0,4	0,4
maximum	0,7	0,7	0,9	0,6	0,9

Table 2: Comparison to standards comfort zone.

Building	A1	A2	B	C	All
Sample size	44	33	70	37	184
Operative temp °C					
% < 23	0,0	0,0	7,1	0,0	2,6
23 <= % <= 26	11,4	0,0	62,9	10,8	28,6
% > 26	88,6	100	30,0	89,2	68,9
Air velocity m/s					
% <= 0,25	59,1	48,5	98,6	54,1	71,9
% > 0,25	40,9	51,5	1,4	45,9	28,1
Effective temp °C					
% < 22,8	0,0	0,0	4,3	0,0	1,5
22,8 <= % <= 26,1	6,8	0,0	71,4	10,8	31,6
% > 26,1	93,2	100	24,3	89,2	66,8
PMV					
% <= -0,5	2,3	0,0	5,7	2,7	3,6
-0,5 < % < 0,5	22,7	3,0	64,3	18,9	33,7
% >= 0,5	75,0	97,0	30,0	78,4	62,8
PPD					
% < 10	22,7	3,0	61,4	18,9	32,7
% >= 10	77,3	97,0	38,6	81,1	67,3
Tc ACA					
% < 10	38,6	6,1	88,6	27,0	49,0
% >= 10	61,4	93,9	11,4	73,0	51,0
Tc ACS					
% < 10	65,9	3,0	90,0	27,0	38,8
% < 20	86,4	12,1	97,1	27,0	57,1
% >= 10	34,1	97,0	10,0	73,0	61,2

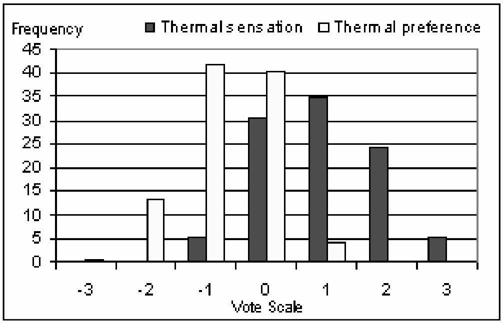

Figure 3: The frequency distribution of votes.

buildings were using local fans during the period of measurements. The indoor air relative humidity fell within the standard comfort limit in all buildings and had a mean of 45,3%.

3.2 Global indoor quality

Concerning the other non thermal indoor measurements, the CO_2 concentration had a mean of 830 ppm, the lighting level a mean of 340 lux, and the sound level a mean of 45 dBA.

The subjects were globally satisfied with the indoor air quality about 56 % of the total observations, 65 % with the lighting quality and 95 % with the sound quality. Subjects preferred to have more air movement on 50 % of the total observations. Windows were open on 54 % of the total observations, and the stores on 37%. On 29 % of the observations, subjects had a ventilator on during the measurements.

3.3 Thermal sensation and preference

Figure 3 shows the distribution of the total population of thermal sensation votes along with the thermal preference votes. The mean sensation vote was on the warm side of neutral in the four buildings. The largest value was in building A2 with a value of 1.5 against 1.2 in A1 and C, and 0.5 in B. This tendency was reflected in the preference vote that had a mean of –0.7 in the four buildings, with more than 40 % of participants want to be cooler.

3.4 Thermal comfort vs. PMV

The mean PMV and mean thermal sensation vote from the sample of the four office build-

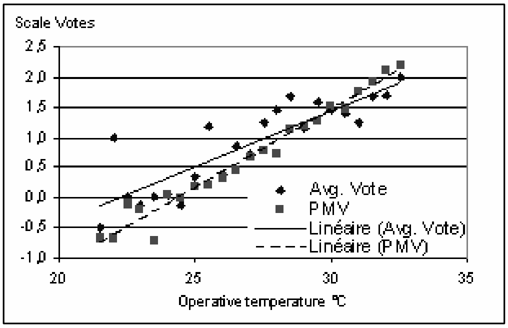

Figure 4: Thermal sensation vote & PMV vs. To.

ings are plotted as a function of the operative temperature in Figure 4. A linear regression was done upon the average vote and PMV, weighted by the number of observations for each value of To. The correlation coefficient of the average vote upon To is 0.82, and the slope of 0.22 unit vote/°C.

The regression line of the average PMV is generally within 0.5 scale units of average thermal sensation regression line. However, when we dress the frequency distribution of the PMV against the thermal sensation vote, it reveals that the PMV overestimated the thermal sensation of subjects in the interval from cool to warm, and underestimated it when it is hot or more.

From the above regression equation, we have determined the neutral temperature by solving for vote equal to zero, which corresponds to a neutral sensation. The found neutral temperature (23.1 °C) is lower than the neutral temperature determined from the PMV regression (24.7°C).

3.5 Thermal comfort vs. ACA

The comfort temperature can be deduced from the globe temperature and thermal sensation vote by using the equation set by McCartney and Nicol (2002):

$T_C = T_G - 2\ (CV\text{-}4)$

where:

T_C: Comfort temperature (°C),
T_G: Indoor Globe temperature (°C),
Cv: Comfort vote form ASHRAE scale.

Cv is determined from the thermal sensation vote scaled from 1 to 7. Comfort temperature has been calculated for every subject, and the mean was plotted as a function of T_{RM80} on Figure 5. On the same figure, the upper limit of the ACA comfort temperature, corresponding to 90% thermal acceptability, is also plotted.

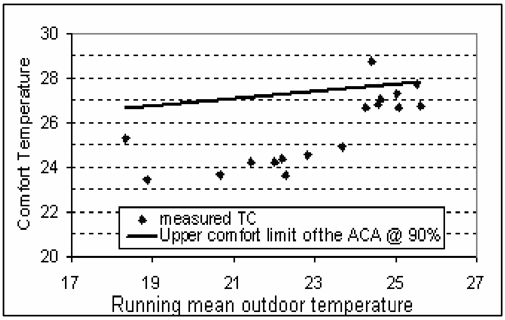

Figure 5: T_C plotted against TRM80.

Figure 5 shows that almost all comfort temperature fall below the upper limit of 90 % acceptability of the ACA comfort temperature, suggesting that the ACA is a good approximation of the thermal comfort for our case studies. The same result was concluded when applying the ACS.

3.6 Use of indoor climate control means

Figures 6 shows the frequencies of comfort vote according to the use of local fans and shading devices. The use of local fans and shading de-

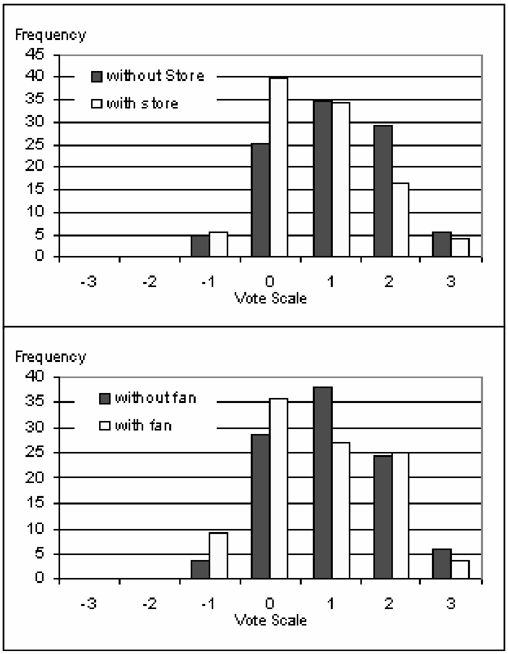

Figure 6: The frequency distribution of comfort vote.

vices has limited the thermal discomfort. In fact, the highest PPD was scored in building C (54%) that has an interior open layout (limiting the access to control means) and building A2 (44%) that has a lack in shading devices.

4. CONCLUSIONS

A field study has been conducted in four NV office buildings in south east of France during the summer 2004. Preliminary findings from analysing the data gathered are as follows:

- The thermal indoor climate was in general warm, and more than the half of the participants were dissatisfied from the indoor thermal conditions.
- The actual thermal comfort standard didn’t match the comfort votes of subjects. The PMV has overestimated the measured thermal sensation in neutral-warm range.
- The application of the new adaptive comfort standard ACS to our data was in close agreement with the measured comfort vote of occupants. It showed that it predicts well the thermal comfort of subjects in naturally ventilated buildings like in our case.
- When applied to our case study, the adaptive control algorithm ACA was also in close agreement with the measured comfort vote of occupants. The application of the ACA to the thermal indoor buildings regulation would result with energy savings with no reduction in the perceived thermal comfort levels. More field studies on other buildings types and outdoor climate conditions are needed to confirm these results.
- Finally, the control of the indoor thermal conditions by occupants was found to have a positive influence on the thermal perception of the indoor climate by occupants. It suggests further work on the role of control means, such as fan and stores, in the interaction between occupants and their environment.

REFERENCES

ASHRAE, 1997. ASHRAE Handbook Fundamentals. Atlanta: American Society of Heating, Refrigerating, and Air Conditioning Engineers, Inc.

de Dear, R.J., 1998. A global database of thermal comfort field experiments. ASHRAE Transactions, vol. 104 (1b): 1141-1152.

de Dear, R.J. and G.S. Brager, 2002. Thermal comfort in naturally ventilated buildings: revisions to ASHRAE Standard 55. Energy and buildings, vol. 34 (6): 549-561.

El Mankibi, M., 2003. Développement et évaluation numérique et expérimentale de stratégies de régulation de la ventilation hybride. Lyon: INSA Lyon.

Gagge, A.P., A.P. Fobelets and L.G. Berglund, 1986. A standard predictive index of human response to the thermal environment. ASHRAE transactions, vol. 92 (1): 709-731.

Humphreys, M.A. and J.F. Nicol, 1998. Understanding the adaptive approach to thermal comfort. ASHRAE Transactions, vol. 104 (1B): 991-1004.

ISO, 2003. ISO Standard 7726: Ergonomics of the thermal environment -- Instruments for measuring physical quantities.

ISO, 2003. ISO Standard 7730: Moderate thermal environments – Determination of the PMV and PPD indices and specification of the conditions for thermal comfort.

ISO, 2003. ISO Standard 9920: Ergonomics of the thermal environment -- Estimation of the thermal insulation and evaporative resistance of a clothing ensemble.

ISO, 2003. ISO Standard 10551: Ergonomics of the thermal environment -- Assessment of the influence of the thermal environment using subjective judgement scales.

McCartney, K.J. and J.F. Nicol, 2002. Developing an adaptive control algorithm for Europe. Energy and buildings, vol. 34 (n. 6): 623-636.

Schiller, G.E., E.A. Arens, F.S. Bauman et al., 1988. A field study of thermal environments and comfort in office buildings. ASHRAE Transactions, vol. 94 (2): 280-308.