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Field Measurements of Perceived Air Quality in the Test-bed for Innovative Climate Conditioning Technologies

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Abstract

Field measurements of perceived air quality were conducted in an experimental test bed for innovative building technologies situated at the Czech Technical University in Prague. The technologies included photocatalytically active paint, vacuum porous insulation and wall plaster containing phase change material. Technologies were installed in eight offices as part of the research project Clear-up. The offices were primarily used to carry out comparative tests for individual technologies. The present paper describes measurements done in parallel to the comparative tests to investigate the potential influence of aforementioned technologies on the perceived air quality. Additionally, the effect of Demand Controlled Ventilation (DCV) on the perceived air quality was tested. Measurements comprised of the assessments of perceived air quality and objective measurements of operative temperature, relative humidity and CO_2 concentration. Results showed that the mean sensory pollution load in the tested offices was 0.09±0.02 olf/m^2 (mean±SEM). This refers to a low-polluting building according to CEN Report CR 1752. The acceptability of the air quality was worst in unoccupied offices ventilated at 20 m^3/h. Application of DCV decreased the CO_2 concentration, but did not result in statistically significant improvement of the perceived air quality. It was not possible to quantify the influence on the sensory pollution load of particular technologies tested as part of the Clear-up. However, the sensory pollution load in unoccupied offices equipped with those technologies was on average 0.07 olf/m^2 lower than in the reference office.

Keywords – perceived air quality, field measurements, sensory pollution load

1. Introduction

Clear-up [1] is a large-scale collaborative project supported by 7th Framework Program of the European Union. The objective of the project was to develop, install, measure and evaluate technological solutions in real world applications to achieve energy savings in existing buildings by using new technologies such as: phase change material plaster PCM [2], photocatalytic paint PCP [3], vacuum insulation panels VIP [1], electrochromic windows [1], light guiding systems, as well as Demand Controlled Ventilation (DCV) based on detection of Carbon Dioxide (CO_2) as well as Volatile Organic Compounds (VOC) [4]. The project included both component development and real life testing. Therefore the important part of the real life testing was the evaluation of the indoor environmental conditions created in the building equipped with the tested innovative technologies.

The work reported in the present paper focused on the perceived air quality in the test spaces (so called Experimental Test Bed of the Clear-up project). Previous research has demonstrated relations between the air quality and comfort, health and productivity of the occupants [5, 6, 7]. The results clearly showed that poor air quality negatively influences human well-being and performance. It is clear that the energy savings resulting from the application of the aforementioned technologies should be reached without sacrificing the health, comfort and performance of the occupants. Therefore the field measurements reported in the present paper were conducted to evaluate whether the technologies tested by the Clear-up project do not cause aggravation of the perceived air quality.

The following two hypotheses were tested: (1) The installation of phase change material plaster PCM, photocatalytic painting PCP and vacuum insulation panels VIP will not result in higher sensory pollution load; (2) Application of Demand Controlled Ventilation driven by the CO_2 concentration will improve the perceived air quality.

2. Methods

2.1 Test offices and ventilation system

The test facility was situated at the Czech Technical University in Prague. The test rooms were offices of the university employees that were adapted for long term testing of the technologies described earlier. Measurements described in the present paper were conducted in four offices with windows facing south-east (Figure 1). The offices had identical dimensions of 5 m x 3.3 m x 2.8 m (length, width and height) and a volume of 46.2 m^3. The floor plan of the offices (further referred to as office 1, 2, 3 and 4) is depicted in Figure 1. Offices 1, 3 and 4 were equipped with the following technologies: PCP (on ceiling), PCM (on internal walls) and VIP (opaque part of the external wall). Office 2 was used as a reference. All offices were equipped with office furniture, computer screen, laptop/desktop computer, printer etc. The floor was covered with short-pile carpet. There was a sanitary corner with a wash-basin in each office.

All offices were equipped with DCV - variable air volume ventilation that was able to provide balanced ventilation with pre heated outside air. No cooling of the ventilation air was available. The ventilation system was equipped with a controller allowing individual temperature settings for each office as well as the following control opportunities for supply/return airflow: constant ventilation, schedule based ventilation and demand controlled ventilation (based on the CO_2 concentration in individual offices).

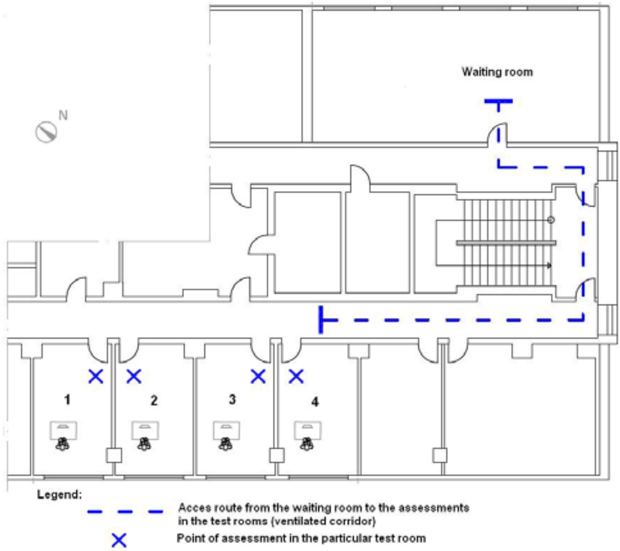

Figure 1. Plan view of the building

2.2 Experimental conditions

Assessments were conducted during three consecutive days in June 2012. Three tested conditions were expected to result in three different levels of perceived air quality in the offices. The conditions are summarized in Table 1. Conditions C1 and C2 were designed to represent a "worst case" with the ventilation system in operation at minimum airflow (air change rate ~ $0.4\ h^{-1}$). In the case of C1 the offices were unoccupied; therefore perceived air quality was expected to be influenced only by building-related sources. C2 represented a scenario with minimum ventilation available and occupied offices. C3 represented CO_2 driven DCV with a set-point of 800 ppm (absolute CO_2 concentration).

Table 1. Examined conditions; Q – air flow set-point, To – operative temperature set-point

Condition	Q [m^3/h]	To [°C][(2)]	Human bioeffluents[(3)]
C1	20	24	No
C2	20	24	Yes
C3	Q=f(CO_2)[(1)]	24	Yes

[(1)] Demand controlled ventilation with set-point CO_2 = 800 ppm
[(2)] Originally it was planned to maintain an air temperature of 24°C during summer conditions, however the ventilation system of the test-bed was not capable of keeping this temperature. This resulted in higher temperatures, which however were similar for all offices (see Table 3)
[(3)] There were two occupants in office 1, 3 and 4. There was only one person in office 2.

2.3 Objective measurements

Objective measurements of indoor environmental parameters included air and operative temperatures (measurement accuracy: ± 0.4°C at 25°C), relative humidity (measurement accuracy: ± 2.5% from 10% to 90%), and CO_2 concentration (calibration range: 0-5000 ppm; measurement accuracy: ±(2 % of range + 2.0 % of reading). For the operative temperature grey sphere shaped sensors were used [8]. As no analytical measurement of the supply and exhaust airflow was possible, the data logged by the building management system (BMS) were used. Air infiltration in the rooms was not measured.

2.4 Sensory assessments

Sensory assessments were performed by a panel of human subjects – students of the University. Characteristics of the sensory panel are summarized in Table 2. Before the experiment started, the subjects were thoroughly instructed about the assessment procedure. All subjects were paid for their participation in the experiment.

The subjects assessed Acceptability of Air Quality (ACC), Odour Intensity (OI), Air Freshness (AF) and air dryness (AD) in each office using Visual Analogue Scales placed on separate paper sheets [9]. Members of the sensory panel were gathered in the well ventilated waiting room and sent to the particular office by the experimenter (see Figure 1). The order of their assessments in the offices was randomized. The assessment was done immediately after entering the office. The doors were kept closed both between and during individual assessments.

2.5 Data treatment and statistical analysis

The percentage of dissatisfied with the air quality was calculated according to Gunnarsen and Fanger [10]. Perceived air quality in decipol was determined according to [11]. The total sensory pollution load was calculated using the comfort model by Fanger [11].

Table 2. Characteristics of the sensory panel; mean±SD

Gender	n	Age [years]	Weight [kg]	Hight [m]
Female	18	23.6±1.3	64.9±12.6	170.5±5.6
Male	7	23.7±0.8	78.6±7.2	179.9±5.0
Total	25	23.7±1.2	67.8±13.5	172.6±7.0

The sensory assessments made on paper scales were digitized twice to avoid gross errors. The statistical software R version 2.5.0 [12] and Statistica version 7 [13] were used to analyze the data. Inspection of Quantile-Quantile plots (QQ-plots) together with Shapiro–Wilk's W test were used to test whether the data were normally distributed. The data were analyzed with paired T-test and with Linear Mixed Effects (lme) model [16]. The p-level for rejection of the Null Hypothesis was set to $p=0.05$. The box-plots (box-whiskers) were used to identify outliers and extreme values in the dataset. Outliers were removed from the data; this resulted in reduction of the number of subjects to 21 (only responses of subjects whose assessments were available for all conditions were analyzed).

3. Results

Results of the measurements are summarized in Table 3. Temperatures and humidity under the different conditions were comparable in all offices. The measured airflow in office 1 was far below the set-point in the case of condition C1. This was most probably caused by the malfunction of the control dampers in the ventilation system.

The acceptability of the air quality for C1 was assessed worst in the case of office 1, 2 and 4. With the presence of occupants, the acceptability of the air quality increased in all offices but the office number 3. The increase was statistically significant in offices 2 and 4 (Table 3). Introduction of DCV in condition C3 resulted in further improvement of the acceptability of the air quality in office 1 ($p<0.01$). In offices 2 and 4 the acceptability remained on the level reached during C2. No significant changes in acceptability in office 3 were observed regardless the tested condition. Odour intensity was in general low in all offices: 15.5±9.1 (mean±SD from all conditions; 0 = no odour, 50 = overpowering odour). No statistically significant changes in odour intensity among tested conditions were observed in offices 2 and 3. DCV (C3) significantly decreased the odour intensity in office 1 ($p<0.05$). In office 4 the odour intensity decreased notably (however the difference in means was on the border of statistical significance; $p=0.053$), but then significantly increased again during C3 ($p<0.05$). Results of the air freshness basically followed the trends of the acceptability of the air quality. Results regarding air dryness indicated that subjects in general perceived the air to be neither too humid nor too dry (with overall mean±SD of 55.1±18.7; 0 = air too humid, 100 = air too dry). The air was perceived as more humid under condition C3. This was significant in office 1 and 2 ($p<0.05$).

4. Discussion

The sensory pollution load for the offices was calculated from the sensory measurements and data on outdoor airflow rates obtained from the BMS system. The calculated sensory pollution loads are summarized in Table 3. CEN Report CR 1752 [15] specifies limits of 0.1 olf/m^2 and 0.2 olf/m^2 for low-polluting and non low-polluting buildings, respectively. The mean sensory pollution load for all evaluated offices was 0.09±0.02 olf/m^2 (mean±SEM). This classifies the building in the low-polluting category. However, it can be seen from Table 3 that the sensory pollution load for particular offices reached over 0.1 olf/m^2 for some of the conditions. During condition C3, office 3 had the highest sensory pollution load observed: 0.28 olf/m^2. The observed values of sensory pollution load are in good agreement with the literature. Wargocki et al. measured sensory pollution loads in six Danish non-smoking office buildings [16]. The sensory pollution loads for occupied building observed in that study ranged from 0.08±0.02 olf/m^2 to 0.37±0.13 olf/m^2 (mean±SEM).

The results of the current study clearly demonstrate the challenge of perceived air quality measurements in real buildings. Although the assessed spaces are used for the same purposes, have in general the same furnishing and equipment, the observed behaviour of the sensory pollution in four closely situated offices was quite different. Moreover, the air flow data provided by the BMS system are burdened with high uncertainty. Accuracy of air flow measurement in BMS systems is usually about ±10%. It is therefore necessary to treat the values of perceived air quality and sensory pollution load calculated using the air flow data with respect to the aforementioned inaccuracy.

The improvement of the perceived air quality in the case of occupied offices is a result, which is not consistent with the literature. In the study of Wargocki et al. [16] the sensory pollution load measured in buildings with occupants present was about 0.08 olf/m^2 higher than the sensory pollution load of unoccupied building. Results of the present study show that during condition C2 the acceptability of the air quality improved despite the presence of occupants. This suggests that the sensory pollution from occupants (human bioeffluents) were not the driving force influencing the sensory perception. Moreover, the use of demand controlled ventilation strategy had a positive effect only in the case of office 1.

Table 3. Results of the sensory assessment and objective measurements (data for directly measured parameters represent mean±SD, data for calculated parameter represent only mean value): ACC – acceptability of air quality (-1 = clearly unacceptable, 1 = clearly acceptable), OI – odour intensity (0 = no odour, 50 = overpowering odour), AF – air freshness (0 = air stuffy, 100 = air fresh), AD – air dryness (0 = air too humid, 100 = air too dry), PD – percentage of dissatisfied with air quality, C – perceived air quality, Ga – sensory pollution load, CO_2 – absolute CO_2 concentration, To – Operative temperature, RH – relative humidity, Qin – supply air flow, Qout – exhaust air flow

Condition	Office	ACC[1]	OI	AF	AD	PD	C	Ga	CO_2	To	RH	Qin	Qout
		[-]	[-]	[-]	[-]	[%]	[dec]	[olf/m²]	[ppm]	[°C]	[%]	[m³/h]	[m³/h]
C1	1	0.04±0.52	15.2±9.1	30.4±22.5	62.2±20.7	41	4.2	0.050	551±25	29.7±0.4	43.3±0.6	7.0±0.3	7.7±2.8
	2	0.02±0.34	20.5±9.4	25.0±16.1	64.4±18.4	43	4.7	0.140	504±14	28.9±0.3	42.7±0.5	17.7±4.7	18.6±3.7
	3	0.17±0.45	16.6±12.7	33.4±21.7	56.6±15.9	26	2.0	0.068	634±38	29.1±0.3	48.1±0.6	19.9±0.6	19.4±1.4
	4	0.13±0.46	13.8±9.9	27.9±12.5	60.0±18.7	30	2.5	0.084	552±25	29.5±0.5	43.8±0.6	20.0±0.9	19.3±2.2
C2	1	0.23±0.40*(0.43)	16.7±10.4	36.3±20.6	55.9±18.1	20	1.4	0.045	971±60	30.7±0.2	48.3±0.4	19.7±3.9	19.8±3.9
	2	0.21±0.28*(0.64)	17.1±6.8	29.4±12.4	57.8±16.7	22	1.6	0.045	932±23	30.5±0.1	47.2±0.1	17.0±5.5	17.6±4.3
	3	0.10±0.31	17.6±8.3	30.2±17.5	48.1±25.4	33	3.0	0.102	1274±61	31.2±0.2	53.2±0.5	20.5±1.9	20.2±1.8
	4	0.36±0.35**(0.57)	9.5±4.7	41.7±18.9	52.4±17.5	11	0.7	0.023	1118±68	30.9±0.1	49.3±0.2	20.0±1.5	20.6±2.3
C3	1	0.46±0.36**(0.96)	9.7±6.7	55.4±21.3	49.2±17.1	7	0.4	0.066	673±23	30±0.3	49.0±0.4	95.2±9.5	94.5±6.9
	2	0.20±0.36⁺	18.6±7.6	41.6±18.4	53.1±17.1	22	1.7	0.068	774±39	29.4±0.1	49.1±0.3	24.5±18.6	25.1±17.3
	3	0.08±0.31	16.5±9.6	27.3±19.0	50.1±17.5	36	3.3	0.283	753±101	30.1±0.1	52.7±0.6	50.3±1.1	50.4±1.8
	4	0.36±0.34*(0.58)	13.7±7.2	41.1±19.8	51.5±16.4	11	0.7	0.053	903±25	29.9±0.1	50.2±0.1	46.2±5.8	46.1±5.8

(1) Result of the statistical analysis comparing mean ACC values from C1 to C2 and C3 is indicated as follows: ⁺ $p \sim 0.05$ result on the border of significance, * $p < 0.05$, ** $p < 0.01$; Number in the brackets indicates effect-size statistics

The increased airflow decreased the CO_2 concentration and resulted also in low percentage of dissatisfied with the air quality (PD = 6%). No such effect was observed in the other offices although the supply airflow increased in all of them. In these offices increased airflow decreased the CO_2 concentration, but the perceived air quality remained unchanged. This again suggested that human bioeffluents were not the strongest sensory irritant. The values of the percentage of dissatisfied for conditions C2 and C3 can be compared to the recommendations by the European Standard EN 15 251 [17] for category II ("normal level of expectation, should be used for new buildings and renovations"). This comparison shows that the ventilation strategies used under C2 and C3 were able to meet the category II requirements (PD = 20%) in all offices but office 3 (Figure 2).

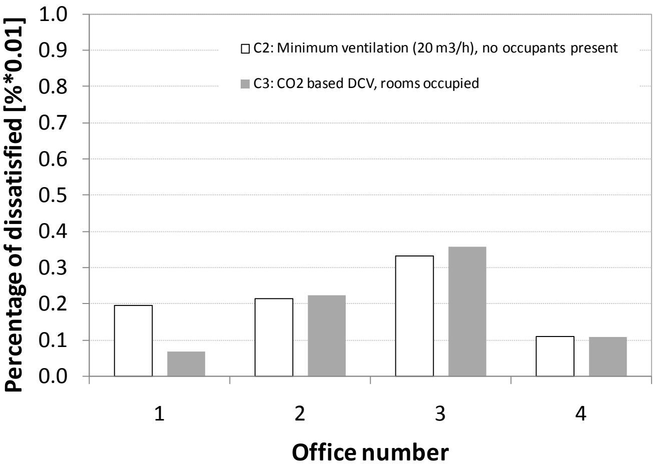

Figure 2. Mean values of the Percentage of dissatisfied with the air quality for conditions C2 and C3, vertical bars indicated standard combined uncertainty according to [18]

It is difficult to estimate the reason for consistently higher percentage of dissatisfied in the office 3. One of the reasons can be that there was a lot of different equipment stored in the office (measuring devices, electronics, installation material etc.) as the occupant is using such equipment in his daily work. However, the precise scientific judgement cannot be done neither on the basis of this observation nor based on the data collected in the present study.

The design of the experimental test bed was subordinated to the technological testing (separate test of ventilation system, testing of the effectiveness of PCM plaster in attenuating temperature peaks etc.) rather than to the indoor air quality research. Due to this fact it was not possible to evaluate separately the effect of the different technologies on sensory pollution load. The quantification of the potential impact of the technologies on the sensory pollution load was therefore limited to the comparison of the sensory pollution load calculated for condition C1 (unoccupied offices). The results are depicted in Figure 3.

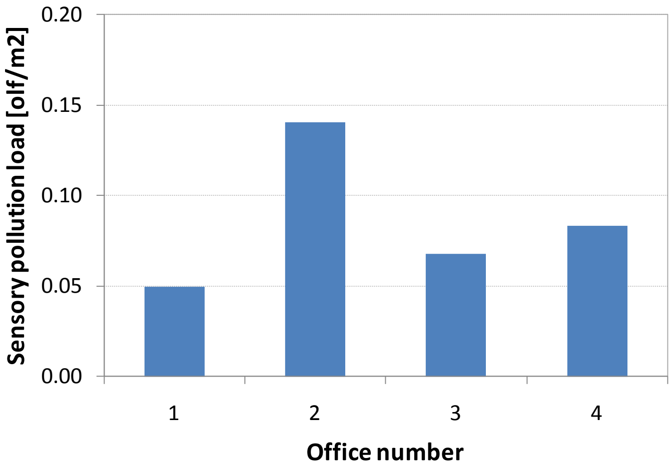

Figure 3. Mean sensory pollution load, condition C1

It is clear from Figure 3 that sensory pollution load for offices where PCO, PCM, and VIP were added was lower than the sensory pollution load in the non equipped (reference) office 2. The average difference is equal to 0.07 olf/m^2. However, it is not possible to state that the lower sensory pollution load in the equipped offices was caused by the presence of the tested technologies.

5. Conclusions

- The mean sensory pollution load in the tested offices was 0.09±0.02 olf/m^2 (mean±SEM). This refers to a low-polluting building according to the present standards.
- The acceptability of the air quality was worst in unoccupied offices ventilated at 0.4 h^{-1}. When the offices were occupied the acceptability of the air quality increased significantly in three out of four of them.
- Application of Demand Controlled Ventilation led to a decrease of the CO_2 concentration, but did not result in

statistically significant improvement of the perceived air quality.

- It was not possible to quantify the influence on sensory pollution load of particular technologies tested as part of the Clear-up. However, the sensory pollution load in unoccupied offices equipped with those technologies was on average 0.07 olf/m^2 lower than in the reference office.

6. Acknowledgment

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