Evaluation of natural ventilation systems in a landscaped office.

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ABSTRACT: The Renson office building (Waregem, Belgium) relies on natural ventilation for both indoor air quality and temperature control. Indoor air quality control is provided by a system consisting of self-regulating inlet vents and passive stack exhausts. Temperature control in summer is achieved by a system for natural night ventilation with motorized inlet and outlet windows.
The indoor air quality and thermal comfort in the offices is evaluated on the basis of long-term measurements of relative humidity, CO_2 and internal temperatures and discussed in the paper.

Conference Topic: 5 Materials and building techniques
Keywords: Natural ventilation, night ventilation, IAQ, thermal comfort

1. INTRODUCTION

1.1 Building description

The low-energy office building of Renson, a company that develops and manufactures natural ventilation and solar shading systems, is located in Waregem (Belgium) in between the manufacture plant and the highway. The office is designed to demonstrate the so-called ‘healthy building concept’, which relies on natural ventilation and solar shading to achieve indoor air quality and temperature control with limited energy consumption (no air circulation and refrigeration equipment).

All offices are located on the second floor on top of a limited ground and first floor with building services. The office floor is supported by 6m high columns, in order to hide the production plant from view. The façade is almost completely glazed. Properties of the insulating glass and other thermal building data are shown in table I. The floor consists of a raised (false) floor system.

Figures 1 and 2 show a plan of the second floor and a vertical section. The office floor consists of an open plan office (n°1), oriented to the north, surrounded by small offices on the south-west side (n°2 and 3), internal (n°4) and external (n°5) meeting rooms on the south-east and north-east side and lunch rooms (n°6). With exception of the external meeting rooms (n°5), which are mechanically ventilated, all other rooms are naturally ventilated.

1.2 Concept natural ventilation and passive cooling

The natural ventilation system for indoor air quality control consists of acoustic self-regulating inlet grills and passive stack exhausts. The inlet grills are located at the bottom of the curtain wall over the full length of the façade (see **Figure 3**). In winter the supply air is heated by the underfloor convector heating system.

Table I: Thermal building data.

	window			
	NO (n°6)	NO(n°5)	NW	ZW
A_{glass} (m²)	75	250	300	225
g (-)	0,61	0,61	0,53	0,53
U (W/m²K)	1,3	1,3	1,3	1,3
LTA (-)	0,76	0,76	0,74	0,74
Sun blades	no	no	no	yes
	floor		roof	
U (W/m²K)	0.5		0.3	
A (m²)	2330		2330	
V (m³)	8388			

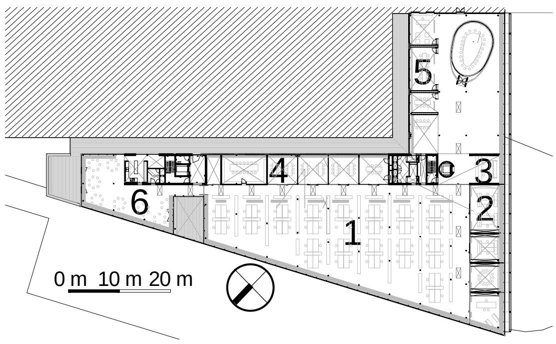


Figure 1: plan of second floor with landscape office (n°1), accounting and management section (n°2), reception desk (n°3), internal (n°4) and external (n°5) conference rooms and service rooms (n°6)

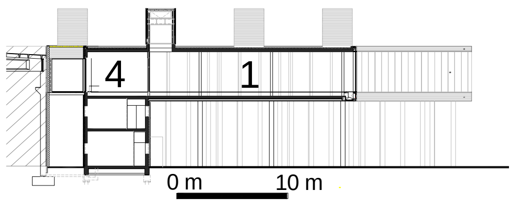


Figure 2: vertical section through landscape office (n°1) and internal conference rooms (n°4)

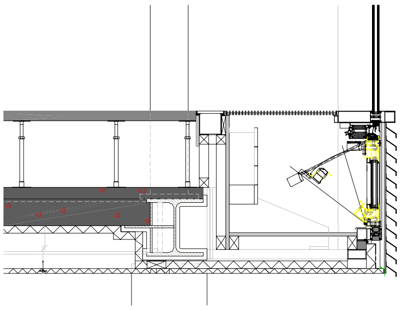


Figure 3: Inlet grill and window for natural day and night ventilation at the bottom of the curtain wall.

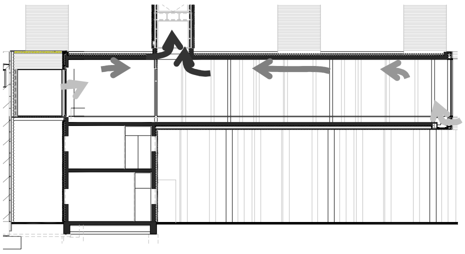


Figure 4: Operation of natural night ventilation.

Table II: Internal heat gains with actual and design occupation in some office rooms.

		landscape (n°1)	**Accounts 1 (n°2)**	**Accounts 2 (n°2)**	**Reception (n°3)**
Area (m²)		992	63	37	35
People	actual	50	4	2	2
	design	85	4	2	2
Office equipment	PC + monitor p.p.	1	1	1	1
	Printers	5	2	2	-
	Fax	2	-	-	1
	Copiers	2	-	-	-
Lighting (W/m²)		8	8	8	8
Heat gains (W/m²)	**actual**	**15.4**	**22.7**	**23.2**	**18.2**
	design	**21.0**	**22.7**	**23.2**	**18.2**

Table III: Internal heat gains of people, office equipment and lighting [1].

Heat gains			**diversity**	
			n°1	**n°2 & 3**
people		80 W/pers.	0.75	1
PC + screen		130 W/pc.	0.75	1
Laser printer	desk	215 W/pc.	-	0.5
	office	320 W/pc.	0.5	-
Fax machine		15 W/pc.	0.5	
Copier		1100 W/pc.	0.3	
lighting		8 W/m²	0.75	

The extraction openings are located in 15 individual chimneys on top of the building, at a height of 7.5 m above the inlet grills.

The natural night ventilation system for temperature control consists of motorised inlet and outlet windows, located at the bottom of the curtain walls and in the chimneys (**Figure 3** and 4). The area of inlet and outlet openings is 2% and 1% of total floor area. They are designed to reach a mean ventilation flow at night of 6 ach. This airflow allows to cool down the exposed concrete ceiling of the office floor (625 kg/m² thermal mass). Both inlet and outlet windows are automatically controlled in response to the control algorithm for night ventilation. The occupants may also individually control the inlet windows if additional airing is desired. In the chimney two windows at opposing sides are present. Depending on wind direction, the window on the leeward side will be automatically opened. The outlet windows also serve a daylighting function (sky lights).

A prerequisite for the feasibility of any night ventilation system for temperature control is a reduced cooling load in the building. The following measures contribute to this: automated external sun blades at the south-west side, energy-efficient lighting and office equipment, a well-insulated roof (Table I) and accessible thermal inertia of the concrete office ceilings. Table II and III report internal heat gains of some interesting rooms. In the actual occupation there is a medium level of internal heat gains in the open plan office and the reception desk and a high level of internal heat gains in the accounting offices. For this reason the accounting offices (as well as the external meeting rooms) are the only rooms where an additional cooling system is installed: an overhead fan-coil unit integrated in a false ceiling.

In order to evaluate the performance and operation of the natural ventilation systems, continuous measurements of temperatures in summer 2003 were taken from the Building Management System (BMS) and analysed. This analysis is the basis to evaluate thermal comfort during summer in the building. In addition to the measurements performed by the BMS, measurements of relative humidity and carbon dioxide were performed in the landscaped office in winter 2004. These measurements are used to evaluate indoor air quality during the heating season.

2. HEATING SEASON

2.1 Indoor climate measurements

In February and March 2004, a measuring campaign was conducted to evaluate the indoor air quality in the landscaped office during wintertime. The inside temperature, relative humidity and carbon dioxide concentration were measured below the chimneys at two opposing sides of the landscaped office. Carbon dioxide concentration was further measured in a convector pit in the vicinity of an inlet grill. Finally the registration of outside temperature and relative humidity took place at a shaded location near the building. All parameters were continuously monitored and stored at 10'-intervals.

The measuring results are illustrated in Table IV and Figure 5. Table IV shows the deciles and medians of the measured values during working hours. The CO_2-measurement in the convector pit was assumed to be representative for the outside concentration. As a result of intensive traffic on the nearby highway, this concentration fluctuated with peaks in the morning and early evening.

Table IV: Statistics of indoor climate measurements during working hours (9:00-17:00), Feb-Mar 2004.

Perc	Outside			Inside		
	θ °C	RH %	CO_2 ppm	θ °C	RH %	CO_2 ppm
10%	2.5	54	365	21.7	22	520
50%	6.6	75	410	22.1	26	590
90%	13.8	88	500	22.5	43	690

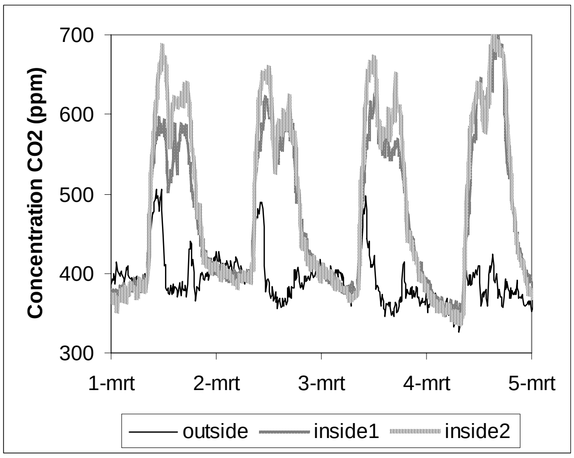
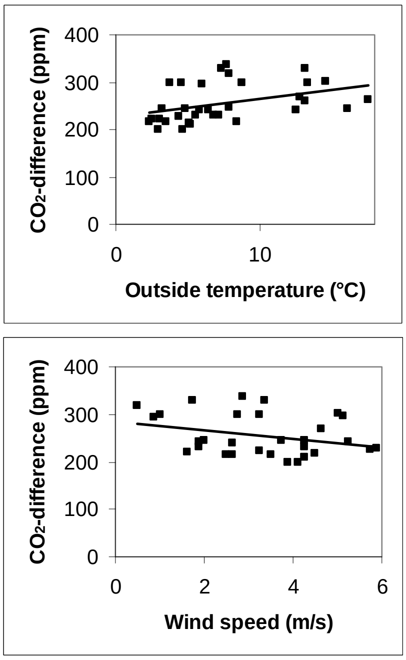


Figure 5: Measured carbon dioxide concentrations.



$$\Delta C = 247 + 7.7 \cdot \theta_e - 13.4 \cdot v \quad (r^2 = 0.47)$$

Figure 6: Relation between the daily maximum inside-outside difference of CO_2-concentration and the mean outside temperature (above) and the wind speed (below).

As Figure 5 shows, during occupation time (9:00-17:00) the indoor concentrations increase to a steady level roughly 250 to 300 ppm above the outside concentration. For comparison, most indoor air quality standards consider a difference of 1200 ppm between inside and outside to be acceptable [2]. Thus the small measured difference between inside and outside concentration is an indication that the outside ventilation rate per occupant is higher than necessary.

This observation is confirmed by the relative humidity measurements. The relative humidity in the landscaped office was found to be smaller than 30% during more than 50% of occupation time. Logically, the lowest values occurred during cold weather. These low values measured in the office may cause complaints of discomfort due to dryness. In order to meet the lower indoor air quality criterion of 30% RH [2], the ventilation rate per occupant should be reduced. This measure may also reduce energy consumption for heating.

2.2 Parameter analysis

As a first indication of the performance of the ventilation system, the relation has been investigated between the indoor air quality and the driving forces for natural ventilation. The daily maximum inside-out side difference of CO_2-concentration is used as an indicator for IAQ. Figure 6 shows the results of the analysis. The concentration difference appears to be remarkably constant: its value remains at a low level, even when outside temperature is high and wind speed is low. This might be the result of interzonal air flow (mixing) between the office and adjacent unoccupied spaces like the lobby and lunch room. The relation between the CO_2-concentration difference and driving forces is not very strong: the coefficient of determination for the multiple regression analysis is smaller than 0.5. There is a slightly positive correlation with the mean outside temperature during occupation time, and a slightly negative correlation with the average wind speed (provided by the BMS). Still the analysis indicates that although the ventilation system has been designed as a thermal stack driven (chimney) system, wind plays an equally important role in the effective ventilation performance. This might explain the unexpectedly low measured values of relative humidity and CO_2-concentration in the office.

The daily measured exponential decay of the inside-outside concentration-difference has been used to quantify the air change rate in the office (concentration-decay method). The air change rate resulting from this analysis was in the order of 0.8 ach, or approximately 60 m^3/h per occupant. In a further step of the research a ventilation model will be applied to confront the experimental with calculation results, and to analyse different measures to improve the performance of the ventilation system.

3. COOLING SEASON [3]

3.1 Natural night ventilation operation

The controls of the night ventilation system are set as follows. The system operates generally from 9 p.m. till 7 a.m. The operation time may be extended in extremely warm summer periods. The operation of natural night ventilation further depends on the maximum inside and outside air temperature of the previous day ($\theta_{i,a,max}$ > 23°C and $\theta_{e,a,max}$ > 22°C), on inside air temperature ($\theta_{i,a}$ > 20°C) and relative humidity (R.V.$_i$ < 70%), wind speed during rain (no wind) and wind speed for storm (v < 50 km/h). When these conditions are fulfilled, the inlet and outlet windows are opened automatically to allow an increased ventilation rate.

The monitoring of the effective performance of the system showed that the system was in operation every night between May 28 and August 27 and 8 days during the second half of September. Control parameters were fine-tuned in this period. Figure 7 shows temperatures, relative humidity and operation of ventilation openings during the first week of a heat wave in August. Highest relative humidity (between 60 and 70%) and lowest temperatures occurred in the morning. Inlet windows were generally opened during the whole night. Outlet windows were separately controlled and opened and closed several times a night.

The performance of the system for night ventilation has been analysed based on the achieved temperature drop overnight (between 9 p.m. and 8 a.m. the next day). Figure 8 shows the temperature drop in the landscaped office as a function of the mean indoor and outdoor temperature difference during night (from 9 p.m. till 8 a.m.).

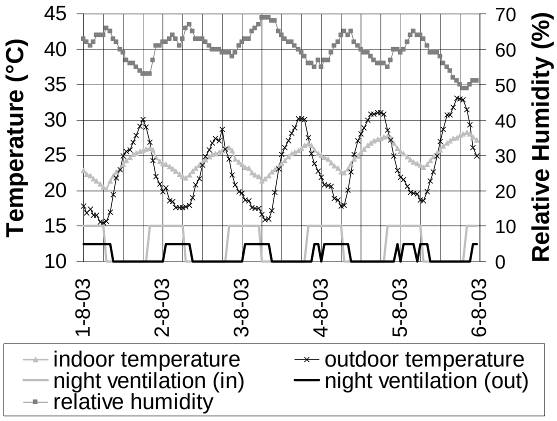


Figure 7: Measured indoor and outdoor temperature, indoor relative humidity and operation of ventilation openings during a heat wave.

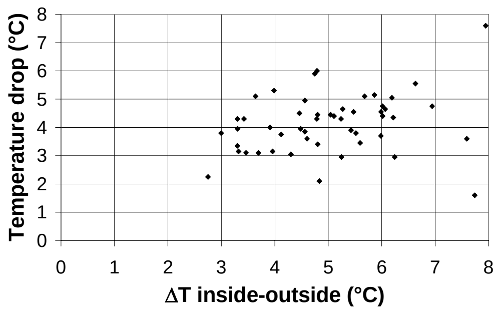


Figure 8: Temperature drop in the landscaped office hardly depends on temperature difference inside - outside.

Table V: Temperature drop overnight in landscaped, reception and accountancy offices

Temperature drop	Mean (°C)	Standard deviation (°C)
Landscape	4.1	1.0
Reception	2.9	1.2
accountants	3.0	1.2

Similar results are noticed for reception and accouncy offices. The average temperature drop in the landscaped office was 4.1°C, it varied between 3.1 and 5.1°C with a probability of 68%. As Table V shows, the temperature drop in the reception and accountancy offices was 1°C smaller, with variations in the same order as in the landscaped office. The mean indoor-outdoor temperature difference during night was minimally 3°C and 2°C with a probability of 0.95 in respectively the open plan office and the reception and accountancy offices when night ventilation was in operation.

3.2 Thermal comfort evaluation

This paragraph will discuss and compare the thermal comfort measured in the open plan office, in the reception desk and the accountancy office. The latter office is the only one provided with a mechanical cooling system.

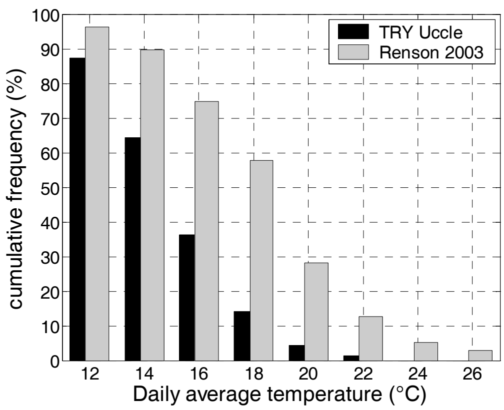


Figure 9: Comparison cumulative daily average outside temperature distributions on site vs Test Reference Year (TRY) Uccle (Belgium).

Measurements from May to September 2003 are used in the analysis. According to the Royal meteorological institute of Belgium (RMI) this period (summer 2003) was extremely warm and sunny [4]. Normal mean outside temperature was exceeded nearly every day. Furthermore during the first two weeks of August a heat wave occurred: temperature peaks of more than 37°C were measured on 4 days. Figure 9 compares the statistics of the daily average external temperatures measured on site to the external temperatures of test reference year (TRY) in Uccle, which are normally used in design calculations to assess thermal comfort. The comparison is in agreement with the conclusions of the RMI.

Two criteria have been used to evaluate the dynamic thermal comfort: (a) the temperature exceeding hours method [5] and (b) the adaptive boundary temperature indicator (ATG) [7] .

Fangers' comfort theory [8] is the basis for the method of temperature exceeding hours. The method limits the working hours in which more than 10% of occupants are dissatisfied (i.e. PPD or predicted percentage of dissatisfied people) to a maximum of 5%, or 100 hours a year (based on 2000 working hours). The critical indoor operative temperature corresponding to a 10% PPD-requirement, depends on metabolism (activity level) and clothing resistance. Assuming seated office work (metabolism = 65 W/m²) and light working clothes (0.7 Clo), a threshold temperature value of 26.0°C is found [6]. As an additional requirement the time during which more than 25% of occupants may be dissatisfied is limited to 1%, or 20 hours a year. The 25%-requirement corresponds to an indoor operative temperature of 28°C.

Figure 10 shows the measured temperature exceeding hours in the open plan, reception and accounting offices. The temperatures in the landscaped office are generally higher than in the other offices because of solar heat gains in the evening: the glazed northwest oriented façade has no sun blades. In the accountancy offices with mechanical cooling the exceeding hours are far reduced compared to the other rooms. In the open plan office daily maximal indoor temperatures occurred in the late afternoon (at 4 or 5 p.m.). In the other offices, with southwest orientation and external solar shading devices, the maximal temperatures were reached during the whole afternoon depending on the actual weather (from 12 a.m. to 5 p.m.).

The measured exceeding hours are 69h, 47h and 34h for respectively the open plan office, reception desk and accountancy office. Compared to the performance criterion of 100 exceeding hours above 26°C, the thermal comfort in all offices proves to be acceptable, especially considering the extremely warm and sunny weather on site. However the additional requirement of maximum 20 exceeding hours above 28°C, is not met in the landscaped office. Here 25 exceeding hours were measured, typically occurring during the August heat wave. Considering the exceptional occurrence of such weather, the deviation between requirement and actual performance is quite small.

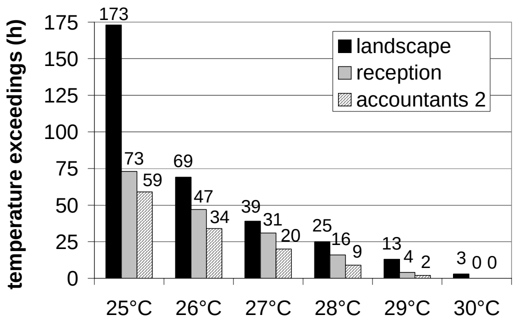


Figure 10: Temperature exceeding hours in landscape office, reception and accountancy offices.

The adaptive boundary temperature indicator (ATG) has been developed in accordance with the adaptive comfort theory of Brager and de Dear [9]. Comfort measurements in naturally ventilated buildings, where occupants are able to open windows and adjust indoor conditions, revealed a stronger relation between the preferred indoor temperature and the prevailing external temperature than Fangers' comfort theory may explain [10]. This is caused by behavioural and psychological thermal adaptation. Behavioural adaptation refers to any conscious or unconscious action a person might make to alter their body's thermal balance, including changing clothes, opening windows, etc. Psychological adaptation on the other hand means that the perception of thermal conditions depends on past experiences and expectations.

The ATG-method distinguishes between three levels of thermal comfort (see Figure 12 for naturally ventilated buildings) [7]. Level A corresponds to 90% thermal acceptability and is applied in buildings with high performance requirements to thermal comfort. Level B corresponds to 80% thermal acceptability and means good indoor thermal comfort. This is the standard level. Level C finally corresponds to 65% thermal acceptability and is only applied in temporary situations in existing buildings.

As derived in the adaptive comfort theory, the minimum and maximum limiting values for indoor temperature on a given day depend on the effective outdoor temperature $T_{e,ref}$, i.e. the running mean outdoor temperature of the given day and three preceding days with weighting factors in sequence of 1, 0.8, 0.4 and 0.2. During an average summer in northwest Europe, a $T_{e,ref}$-value of 16°C corresponds to a normal summer period, while $T_{e,ref}$ reaches a maximum value of 22°C corresponding to a warm summer period.

Figure 11 and 12 show the measured daily maximum and minimum indoor temperatures during occupancy, compared to the adaptive boundary temperature indicator. The application of the ATG-method to the measured maximum temperatures, confirms the conclusions of the temperature exceeding method. The observed thermal comfort is good (Level A or B) as long as outdoor temperatures are not abnormally high ($T_{e,ref}$ < 25°C). Only during the August heat wave with running mean outdoor temperatures above 26°C, the acceptability level of 65% is not met in the landscaped office over 3 days.

The analysis of the measured minimum temperatures during occupancy reveals a more systematic comfort problem. The operative temperatures occurring at 8 a.m. when occupants arrive are often smaller than the 65%-acceptability limits derived in the ATG-method. This is caused by an inadequate set point in the night ventilation control algorithm that might cause complaints of discomfort.

During the measurements, the inside temperature set-point for closing the inlet and outlet windows was set at 20°C in the landscaped office and 19°C in reception and accountancy offices. To solve the problem and achieve a good indoor comfort (level B) this set point should be raised to higher values of 20.5 to 21°C.

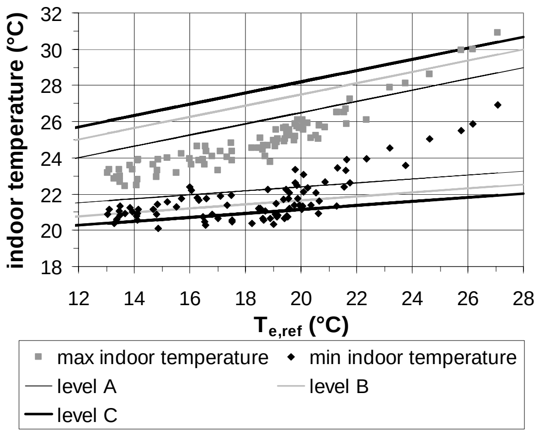


Figure 11: Adaptive boundary temperature indicator in the landscape office.

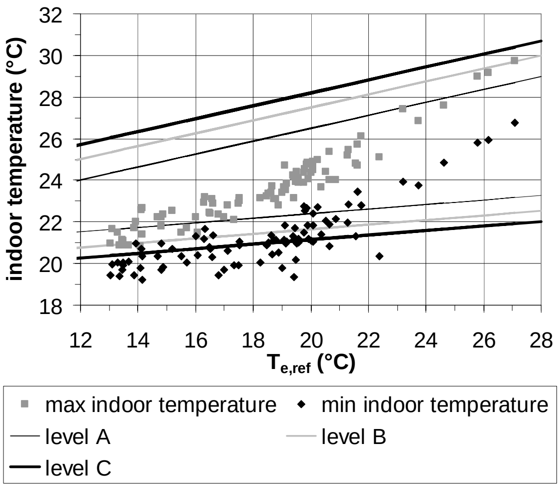


Figure 12: Adaptive boundary temperature indicator in the reception desk.

4. CONCLUSION

The Renson office building relies on natural ventilation and solar shading to achieve indoor air quality and temperature control with limited energy consumption (no air circulation and refrigeration equipment). The performance and operation of the natural ventilation systems has been evaluated on the basis of long-term measurements of relative humidity, CO_2 and internal temperatures.

Measurements of relative humidity and carbon dioxide during winter 2004 showed that ventilation rates per occupant are higher than necessary. As a result humidity in the landscaped office was often too dry. A regression analysis indicated that although the ventilation system was designed as a thermal stack driven (chimney) system, wind played an equally important role in the effective ventilation performance. A modelling analysis is needed to evaluate different measures to improve the performance of the ventilation system.

Measurements of temperatures in summer 2003 were taken from the Building Management System (BMS) and analysed to evaluate thermal comfort during summer. Comfort assessment has been performed by means of the temperature exceeding hours method and the adaptive boundary temperature indicator. The analysis showed the ability of the natural night ventilation system to achieve good thermal comfort, except when outside weather was exceptionally warm, as during the August heat wave. The analysis further showed the need to raise the night ventilation control set point, in order to prevent too low temperatures in the morning.

5. ACKNOWLEDGEMENT

The authors would like to acknowledge the company Renson and in particular dr.ir. Ivan Pollet for the availability of measuring data and their support to additional measurements and research. Also the information on ATG provided by ir. A.C. van der Linden (Technical University Delft) is gratefully acknowledged.

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