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Investigation of indoor climate in a naturally ventilated office building

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SUMMARY
A measuring program in a naturally ventilated office building in Copenhagen was carried out to document the indoor climate and ventilation system performance during a year. It included a questionnaire regarding the perceived indoor environmental quality and physical measurements of thermal comfort, indoor air quality, air distribution in the building, air flow rates and infiltration.

The results showed that the temperature levels in general fulfilled the requirements for thermal comfort. In some parts of the building occupants complained of high and varying temperatures and draught. This was due to a combination of poor control of solar shading and a very high local heat load that was above the Danish recommendations for naturally ventilated office buildings. Both measured and perceived indoor air quality in the building was in general very high. The measured air flow rates was relatively high due to the need for cooling in the office building, while the level of infiltration was quite low indicating an airtight construction.

KEY WORDS
Full-scale measurements, Air quality, Thermal comfort, Air distribution, Infiltration

INTRODUCTION
Even though the main stream in the Danish building industry is going towards airtight buildings with mechanical ventilation, it is important not to leave out the possibility of natural ventilation. This type of ventilation can also provide excellent indoor air quality and thermal comfort - with low energy consumption as an added bonus.

To ensure a proper function of a naturally ventilated building where draught, overheating and poor air quality is avoided, it is important to take the use of natural ventilation into consideration at an early state in the planning process of the building. Here considerations regarding e.g. orientation of the building, internal heat loads and position of workplaces are necessary.

The purpose of the work presented in this paper is to investigate if natural ventilation by window openings in the façade can be an acceptable ventilation strategy in open plan offices. The investigations were made in a naturally ventilated office building in Copenhagen, Denmark, where a measuring program was used to document the indoor climate and ventilation system performance from July 2005 – June 2006. The program both included a questionnaire for investigations of the perceived indoor environmental quality and measurements of thermal comfort and indoor air quality in general and at two selected work stations. Also measurements of air distribution, air flow rates and infiltration were carried out. This combination of physical measurements and questionnaires was used to document the performance of the system and to investigate whether an acceptable indoor climate was achieved by the natural ventilation system.

METHODS

The investigations of the indoor climate in the office building contained both a questionnaire and some indoor environmental measurements. The measurements were divided into long-term measurements where data were collected through out the year and analysed continuously, and short-term measurements where two zones in the office building were selected for detailed investigations during one week in winter, summer and spring. The contents of the different parts of the measuring program are described below, after a short description of the office building. (Larsen et al., 2006)

Building description and function of the natural ventilation system

The office building is a five-storeyed house. The ground floor is mechanically ventilated. Second to fifth floors are naturally ventilated. The office space is positioned around a central atrium with a glassed roof with window openings and automatic solar shading. All façades have the same window distribution, and all windows have a manually and an automatically controlled part. The principle of the floor plan is shown in Figure 1.

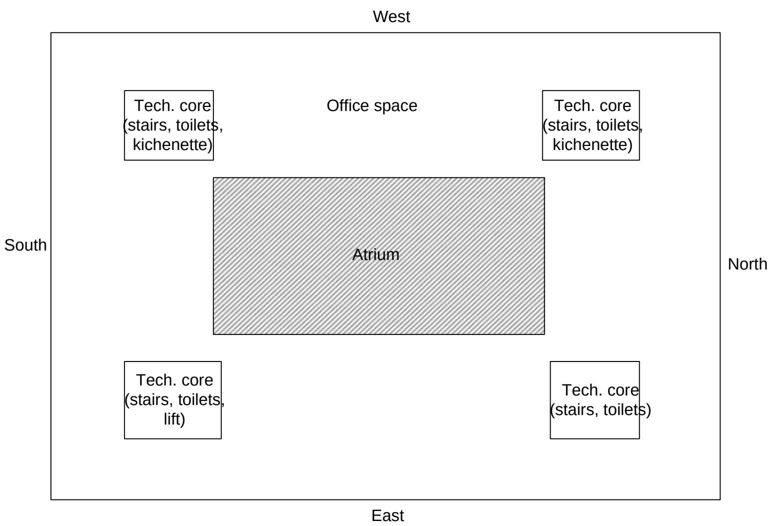

Figure 1. The floor plan (principle).

Each floor is divided into 14 zones controlled by an automatic control system from measurements of temperature (all zones) and CO_2 (four zones at each floor).

Questionnaire

Shortly after the start of the program a questionnaire was distributed to all employees (app. 650 persons) in the office building. The questions regarded e.g. a general evaluation of the indoor climate in the building, descriptions of problems with draught, high temperatures, air quality, daylight, noise and their own personal possibility to change the parameters close to their own workspace.

Long-term measurements

Long-term measurements of room temperature and CO_2 level were made by the automatic control system. Data from 18 different zones in the building (4-5 zones at each floor) were taken out of the system and analysed continuously during the measuring period. The results were held up against recommendations from the Danish regulations. The main features are:

Indoor temperature (DS474, 1993):
Not more than 100 hours above 26°C
Not more than 25 hours above 27°C

CO_2 (Danish Working Environment Authority, 2001):
Below 1000 ppm

Values were measured every 10 minutes, but an average value was calculated for each hour between 8 a.m. and 4 p.m., which was defined as the working hours. It was these values that were held up against the regulations.

Short-term measurements

The short-term measurements were carried out during three periods of one week duration to ensure that typical summer, winter and spring/autumn situations were covered. The measurements made in the short-term periods contained measurements of thermal comfort and indoor air quality in two different zones (selected on the basis of results from the questionnaires) together with an estimate of the local air change rate. In the same periods, measurements of air distribution, air flow rates and infiltration in the entire building were also carried out. An overview of the measurements is seen in Table 1.

Table 1. Measurements carried out during each short-term visit in the building.

Parameter	***Measurements/evaluations***
Thermal comfort	Room temperature Temperature gradients Draught Internal heat load Solar shading
Indoor air quality	Evaluation of the air quality by CO_2
Ventilation capacity	Infiltration Building air change rate during service hours Local air change rate Air distribution between floors

During the measurements also the outdoor temperature, wind speed, wind direction and rain/dry weather were measured to be able to compare these parameters with the indoor measurements, and also to evaluate how the outdoor parameters influence the indoor climate.

Description of the zones used during the short-term measurements

Two zones (A & B) were chosen for detailed measurements of the indoor climate. Zone A (44 m^2) was positioned towards west on the second floor. This area was chosen because of complaints of draught. It had 3 workplaces all with computers, desk lamps and general lighting. The total heat load was 15 W/m^2. Zone B (34 m^2) was chosen because of complaints of high temperature. This zone was positioned on fourth floor and was facing south-east. The zone had 6 workplaces which also were equipped with computers and desk lamps. Besides this, general lighting was used. Here, the heat load was estimated to 34 W/m^2.

RESULTS

Data from the long-term measurements were collected during the entire one-year-period of the measuring program. To spot any specific points of interests, and also get a general view of the indoor climate in the building, a questionnaire was distributed to the employees in the beginning of the program period. Further investigations of the results were made especially during the short-term measurements, but also in some parts of the long-term measurements. The final results will be described in the following sections.

Questionnaire

366 questionnaires were returned after the survey regarding the indoor environmental climate in the office building. This corresponds to a response rate of 56%. During the data processing the building was divided into eight zones depending on the orientation (N, NE, E, SE, S, SW, W, NW). The main results found from the questionnaires were:

Temperature variations

One of the questions regarded the temperature level in the offices. The respondents should tell their opinions of whether the temperature in the office was too high, too low or too varying. In the question regarding varying temperatures, the average number of dissatisfied in the entire building was 20%, but in the south-western zones 55% were dissatisfied. The reason for this was the orientation of these offices where the sun came into the offices during a large period of the day. This did not have to be a problem in itself but the problem arose because of insufficient use of the manually operated solar shadings. The shadings were only used in the case where an employee was directly hit by the sun.

Draught

Another problem that became clear after the survey was that zones with a high heat gain also had problems with draught. Here, the reason was that a high gain requires a higher ventilation rate to remove the heat. Hereby the automatically controlled windows opened more and thereby caused draught. From this result, and later on also seen in the short-term measurements, it was concluded that it is important to a) use the external solar shadings and b) plan the distribution of workplaces in order to avoid too crowded areas with high internal heat gain as a result.

Air quality

On the question regarding air quality in the offices, 85% of the respondents were satisfied. This corresponds very well to the general conception of natural ventilation as a provider of clean air.

Daylight

Also the daylight in the offices was positively evaluated. Here the number of dissatisfied was around 5%. The main reason for this good daylight distribution is the high number of windows, and also their high position in the outer wall. Furthermore, the atrium also provides the offices with plenty of daylight, and the zones with low levels of daylight are thereby considerably reduced.

Noise

One of the main concerns before designing and constructing a naturally ventilated building is often the disturbance coming from noise outside the building. It is not possible to shut all the windows due to noise, because the ventilation system then will shut down at the same time. In the present case the building was situated quite near an elevated railway with trains passing by approximately every ten minutes. Therefore, the result of the questions regarding noise also came out with a surprising result. Only 3% were dissatisfied with noise coming from outside, but 60% were dissatisfied with noise coming from inside the building. This result also show a general problem in open plan offices where noise from your colleagues often is one of the largest annoyance factors.

Long-term measurements
The long-term measurements taken from the automatic control system in general showed a satisfactorily level of both the air temperature and the air quality based on evaluation of the CO_2 level.

The average value of hours with a temperature above 26°C was found to be 52 hours (based on 18 different zones), which was good compared to the recommended "*100 hours above 26°C*" from the Danish regulations. Two zones were locally having approximately 120 hours above 26°C. The reason for this was a high density of persons in these two zones and thereby a high internal heat gain. All zones were below the recommended "*25 hours above 27°C*".

As indicated in the questionnaires the air quality in the building was good. This was also found in the measurements of CO_2 where the CO_2 level only exceeded 1000 ppm a few hours during the entire period of the measuring program. The exceeding was found during winter where the air change rate was minimized due to the temperature level in the offices.

Short-term measurements
During the short-term measurement the greater part of the measurements was focused on local measurements in zones A and B as described earlier. Common for both zones was that the air quality during all seasons was fine with CO_2 levels between 500-800 ppm (highest during winter), and that the relative humidity (RH) also had an acceptable level (25-55%). The RH of 25% was measured during winter due to a low outdoor temperature. The observations regarding thermal comfort and local air change rates differed in the two zones as described below.

Results from zone A
Evaluation of the thermal comfort in zone A showed that comfort temperatures were achieved during all seasons, even though they were a little high (25°C) during the winter period where the system is controlled by the CO_2 level in the building. The highest local air velocities in the zone were measured during the winter period to be 20 cm/s. This corresponds to 20% dissatisfied. The highest local air change rate was found during summer to be $6h^{-1}$. The necessary air change rate was calculated to 1.1 h^{-1} due to CO_2, but because of the internal heat gain and solar gains this was raised by the automatic control system in order to obtain comfort temperatures. During winter and spring this difference between the calculated and the measured air change rate was reduced to a difference of approximately 50%.

Results from zone B
In zone B the temperatures in the occupied zone were also acceptable but close to the upper limit defined for comfort temperatures during summer and winter, respectively. During evaluations of draught, the local air velocities were found to be as high as 25 cm/s during summer. This is caused by a need of high air flow rates in this zone due to the high internal heat gain. The internal heat load was estimated to 34 W/m^2, which is above the Danish recommendations for naturally ventilated office buildings (Danish Building and Urban Research, 2002). In these recommendations the limit is stated to be 30 W/m^2. Above this limit special considerations need to be taken into consideration before using natural ventilation.

In zone B the highest local air change rate was also found during summer. Here it was found to be $5h^{-1}$ and the necessary air change rate was calculated to be $1.5\ h^{-1}$ due to CO_2. This difference between calculated and measured air change rate was also here reduced during winter and spring.

Average air change rate in the building

The average air change rate in the building was measured to be between $3h^{-1}$ and $5h^{-1}$. The necessary air change rate based on the CO_2 level in the building should only have been $0.5h^{-1}$. Also here the air change rate is fairly high due to the high internal gains in the building, which is the reason for the good indoor air quality in the building.

Air distribution

The air distribution between the floors in the building was evaluated from the CO_2 gradients and temperature gradients in the building. The CO_2 values had minor increases on each floor up through the building and the temperatures measured evenly distributed up through the atrium (from 2.2 m above floor to 20 m above floor) also showed a good mixing of air in the building with a temperature gradient in winter at only 0.2°C/m. This is illustrated in Figure 2.

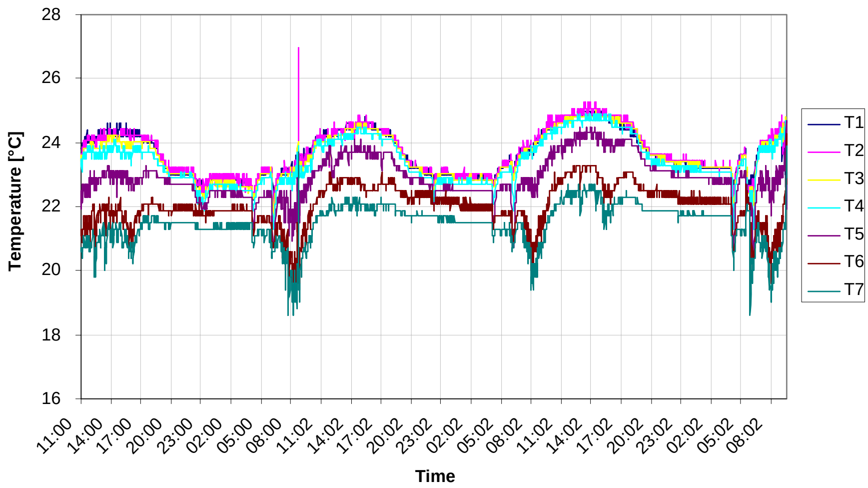

Figure 2. Temperature distribution in the atrium from 2.2 m above floor (T7) to 20 m above floor (T1).

Infiltration

The infiltration in the building was measured in two of the short-term periods using the decay method after working hours. In summer the air change rate due to infiltration was found to be $0.05\ h^{-1}$. The temperature difference between indoor and outdoor was in this case 5°C and the wind speed 1.5 m/s. During the spring period the air change rate was found to be $0.16\ h^{-1}$. In this period the temperature difference between indoor and outdoor was 16°C and the wind speed was 3.3 m/s. As it is seen in both situations the infiltration is very low, indicating that the construction is very airtight, even though it has several windows in the façade.

DISCUSSION

During the measuring in the office building an overall good achievement of thermal comfort was found, but certain zones in the building had problems with high temperatures and draught. The draught was caused by an increased need for cooling in the zones, and thereby more fresh and cold air coming through the windows. This situation could have been avoided if the arrangement of desks, and thereby internal heat gains, in the office area had been considered earlier. Here areas with an internal heat gain higher than $30W/m^2$ should have been avoided.

Another problem in some parts of the building was the varying temperatures due to a poor control of the solar shadings. This problem could easily have been handled by informing the users of the building who needed to know the importance of using the solar shadings in order to use them actively.

CONCLUSIONS

From the survey and measurements made in this work, it is found that good thermal comfort and excellent perceived indoor air quality can be obtained in a building with open plan offices ventilated by natural ventilation by window openings in the façade. The results showed that the temperature levels in general fulfilled the Danish requirements for thermal comfort.

The work also showed that naturally ventilated buildings require integration of the ventilation strategy at an early stage in the building design. Considerations regarding arrangement of the workplaces are important to avoid too high internal heat gain pr. m^2, which might cause thermal discomfort with overheating and draught.

During the short-term measurement periods in the building, and also from results of the questionnaires, it was also concluded that simple guidance for the users is important to obtain an optimum use of e.g. solar shadings and manual opening of the windows. This guidance will help to improve the efficiency of the natural ventilation at the workplaces.

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