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Optimising the position of combined sensors in a typical open plan naturally ventilated office

Baijia Huang
MSc. Low Carbon Building Design and Modelling, Loughborough University, UK,
email: baijiahuang@gmail.com

Abstract
Pressing environmental issues have led to an increasing demand for energy efficient and low carbon solutions to the built environment. Building engineers are reconsidering natural ventilation rather than mechanical ventilation and air conditioning. However, due to the fact that natural ventilation is driven by buoyancy and wind forces, its control presents challenges. This research project addresses the issue of natural ventilation control by optimising the position of combined temperature and CO_2 sensors in an open plan naturally ventilated office, in order to maintain acceptable indoor air quality(IAQ) and thermal comfort. This is achieved by using Computational Fluid Dynamics (CFD), where the distributions of temperature and CO_2 concentration of a case study office have been simulated. Based on the CFD results, this research project will provide guidelines for the locations of combined sensors in the case study office and other naturally ventilated open plan offices.

Keywords: natural ventilation, sensors, DCV, CFD, simulation

1 Introduction
Natural ventilation has recently come back into use, because climate change has prompted building engineers to find alternatives to mechanical ventilation and full air conditioning. However, natural ventilation is driven by buoyancy and wind forces, which are difficult to predict and control. Many control systems use sensors to ensure a good indoor climate is delivered, but these sensors are frequently found in many inappropriate locations which can lead to an uncomfortable indoor climate. This paper reports on research that attempts to solve the problem by identifying optimal locations for combined sensors in a typical open plan naturally ventilated office.

2 Demand-controlled ventilation and sensor locations
Generally speaking, a sensor is a device that detects and/or measures a variable, such as temperature, CO_2 and humidity etc. and transmits its value to the controller so it can act on the information received(Race 2005). Therefore, sensors form a vital component of any control system. A "Demand-Controlled Ventilation" (DCV) system is defined as a type of ventilation system with feed-back and/or feed-forward control of air flow rates, according to a measured demand indicator(Maripuu 2011). CO_2 sensors are often used to detect indoor air quality, whereas temperature only sensors or temperature and humidity combined sensors are used to determine thermal comfort. Much of the literature and studies on sensor based DCV have been reviewed and only few have provided detailed suggestions on the sensor locations. Stymne et al.(1990) investigated the proper location for DCV sensors within a test room, and recommended that the sensors are placed at mid-height and away from doorways, radiators, windows, people and air inlet devices if possible. The follow-up study by Stymne et al.(1991) suggests that sensors should be positioned at occupants' breathing height, approximately 1.1m above the floor. Steiger et al. (2008) has reported the

findings of a test in a naturally ventilated narrow room to simulate a real classroom. His study concludes that in naturally ventilated rooms, it is not appropriate to position sensors near the floor, ceiling and windows. They should be placed on walls at breathing height or higher, at a good distance from windows or other openings, similar to the suggestions above from non-naturally ventilated buildings.

3 Methodology

Due to the nature of natural ventilation, the flow rates cannot be as closely controlled as in mechanical ventilation and air conditioning. Therefore, computer modelling is often used to predict the performance of a naturally ventilated building design (Cropper et al. 2008). Computational Fluid Dynamics (CFD) has been used for modelling the open plan office in this paper, because it is an useful and widely recognized technique for predicting the airflow patterns of natural ventilation, and existing studies already validated the technique and its accuracy. The CFD code used for this work was PHOENICS (CHAM 2008). This is a general-purpose CFD package with a Heating, Ventilation and Air Conditioning interface called FLAIR.

The following settings are used for the simulations. Buoyancy is modelled by the Boussinesq Approximation. This model neglects the density variations in inertia terms in governing equation of motion, but those in buoyancy force term are retained (Cook 1998). The reference pressure is set to be the atmospheric pressure of 101,325.0 Pa. The relative ambient pressure is 0 and it will be initialized from ambient conditions. The ambient temperature is set according to the case scenario. The domain material is chosen to be air at 20°C. Probe position (monitoring point) is set to x=17.43, y=3.99, z=0.875. A medium grid size of x=102, y=65, z=29 is applied.

The case study modelled is an open plan office on the first floor of a converted industrial building near Lichfield, UK. The building owners installed a demand-controlled natural ventilation system in 2011. The indoor climate in the office is monitored by seven combined temperature, relative humidity and CO_2 sensors whose locations will be optimised. However, relative humidity is not usually a major concern in the British climate and therefore, this paper focuses on the temperature and CO_2 distribution. The optimal locations are identified based on four operating scenarios as shown in Table 1. Only winter and summer conditions are being investigated, because it is easier to provide a good indoor climate in the mild British autumns and springs.

Table 1 The simulation scenarios

Cases	Operating conditions
A1	Summer, 21°C, all openings are fully open, 35 occupants, lighting on
B1	Summer, 27°C, all openings are fully open, 35 occupants, lighting on
C1	Winter, 5°C, all openings are 5% open of its full capacity, 35 occupants, lighting on
D1	Winter, 5°C, all openings are 10% open of its full capacity, 35 occupants, lighting on

The model domain is defined to be 23.25m×16.1m×6.505m. The ceiling is modelled by a thin partition with zero thickness at a height of 2.505m. Two stairwell voids and the elevator are modelled as solid blocks. A glass conference room is modelled by two thin plates standing vertically leaving a door-width space for air to circulate. The attic space is defined using two wedge-shaped blocks to simulate the sloping roof. The geometry of the windows is set by the free opening area of the windows to simulate a more realistic airflow. The controllable ceiling tiles are modelled as holes between the ceiling plates. The two roof vents are modelled as regions of fixed pressure, where the flow is usually unspecified but depends on the local pressure difference. All openings have the same boundary conditions: ambient temperature and pressure, a quadratic loss coefficient of 2.69. The velocity is assumed the same as the incoming stream velocity at the windows and same as the upstream velocity at the roof vents.

Each occupant when seated and doing light office work emits 115W according to CIBSE Guide A(Butcher 2006), an average desk PC and monitor together give out 125W/unit. The lighting generates approximately 18W/m^2. Each lamp on the ceiling is modelled as a zero-thickness plate with a surface heat flux. Each cluster of desks and PCs is represented as a rectangular block. These blocks are modelled as constant heat fluxes, to allow air travel through them as it would over and under the desks in reality, the heat fluxes represent the convective heat gains from the PCs. Each seated occupant is modelled as a solid block with a height of 1.2m, and a surface heat flux for the convective component of the occupant heat gains. The radiant component of heat gains from lighting, PCs and occupants is evenly distributed around the floors, walls and ceiling of the space, and represented by setting constant surface heat fluxes.

Outdoor CO_2 concentration is measured to be 393.77ppm in July 2012 (NOAA 2012). This is converted in to a mass fraction, 5.905×10^{-4} kgCO_2/kg of air, which is entered as the initial value for CO_2 and the external value for boundary conditions at all the openings. 2D user-defined objects are used to represent occupants' mouths. Each "mouth" is 0.1m×0.1m in size. A fixed flux of CO_2 per area and a velocity in a momentum source are needed to simulate CO_2 production from a mouth. A simple method of obtaining the CO_2 flow rate is found using the following equation suggested by Awbi (2008) : $\mathrm{G} = 4 \times 10^{-5}\mathrm{MA}$, where G is CO_2 production in l/s, M is metabolic rate in W/m^2 and A is body surface area in m^2. For an average sedentary adult M=70W/ m^2, A=1.8m^2. This equation gives a solution of $6.048 \times 10^{-6}\mathrm{kg/s}$. Therefore, $6.048 \times 10^{-4}\mathrm{kg/s/m^2}$ of CO_2 is produced by one mouth. The velocity is $0.0118\mathrm{m/s}$, calculated based on a few respiratory assumptions: the average adult takes 15 breaths per minute, and each breath has 0.472litres of air.

Both standard k-ε and the RNG k-ε models produce results that show close agreement to experimental or theoretical values in naturally ventilated spaces(Walker et al. 2011)(Cook & Lomas 1997). However, although the RNG k-ε model predicts better quantitative results, it produces higher residuals in the enthalpy equation than the standard k-ε, which often indicates that the equation has not properly converged (Cook & Lomas 1997). Therefore, the commonly used standard k-ε model of Launder and Spalding (1974) is used for the simulations. The buoyancy effect on turbulence is used on automatic control with a relaxation of 0.3.

When using CFD, it is necessary to test for convergence which means the numerical models have been solved satisfactorily with small errors. Cook (1998) has suggested two criteria to evaluate the convergence: 1. The enthalpy residual in the units of Watts should be less than 1% of the total heat gains entering the domain, and 2. The absolute values at the monitoring point should not change by more than 0.1%. Relaxation can often facilitate convergence, therefore it is imposed in the form of false-time step of 0.1 s on the three momentum equations, and 1 s on the CO_2 conservation equation. A linear relaxation of 1 is applied to the temperature and pressure. The automatic convergence control is also used along with the relaxation factors, as this method has been found to give the most consistent convergence.

4 Results

All four cases showed convergence after 10000 iterations. The monitoring plots show stable values of the variable. The changes to all values at probe position are less than

0.1%. The enthalpy residual found in the result file for A1, B1, C1 and D1 are 0.005%, 0.0066%, 0.004% and 0.02% respectively, of the total heat input for each case. This is calculated by finding the fraction of the enthalpy residual out of the total heat gains.

The CFD results for each operating condition is validated with field measurements taken by Khatami (2011) who investigated the thermal comfort and indoor air quality of the same open plan office. To test if the model works properly, there should be a clear increase in the CO_2 level in the space when the ventilation rate is reduced, or matches the field measurements. The measurement data shows a CO_2 at 1030ppm, 1180ppm and 990ppm on three different days when openings are fully closed in winter. At the same location, the simulation result shows the CO_2 concentration at 1029ppm. The result matches field measurement with slight deviations on different days. This provides evidence of a working model that is then further validated by summer measurements. In Case A1 and B1, CFD results show a close correlation to measurement values and a much lower CO_2 value than the winter scenario.

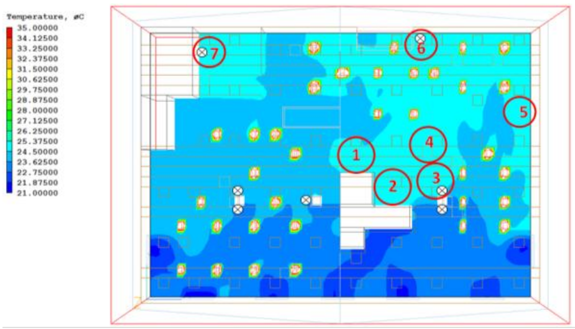

Figure 1 Temperature distribution of Case A1

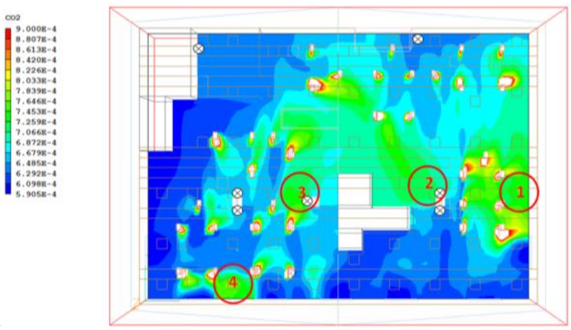

Figure 2 CO_2 distribution of Case A1

All results of temperature and CO_2 distribution are presented in the z-plane view at a height of 1.1m. Case A1 temperature distribution is shown in Figure 1. The symbol ⊗ marks the locations of existing sensors. Three of them are already positioned in the high temperature locations. A few more possible optimal locations are identified and marked by red circles. The first half of the office near the openings (dark blue contours) has lower temperatures than the majority of the office. This shows that the temperature fluctuates near the openings and often is lower than the actual occupied space and therefore, not suitable as a sensor location. Location 4 is at a good distance away from occupants, heat sources and openings. It is thought to be an optimal location for combined sensors, because the temperature and CO_2 concentration are most consistently high at this area; however, not feasible for the case study office due to the lacking of columns. Location 2 requires careful positioning as there is an internal door leading to the staircase, frequent air circulation might occur around that area which is not seen on the CFD result. Figure 2 shows that CO_2 is much less evenly distributed than air temperature, the concentration level can vary significantly in different regions of the office. It also shows that two of the sensors are already located in appropriate places to detect high concentration (locations 2 and 3). A few potential optimal sensor locations have been marked by red circles. When viewed in x, y-planes, the CO_2 concentration at the height of 1.1m seems to be the highest in comparison to other heights. Location 1 gives the best representation of the CO_2 level at the "accounts" area. Location 4 shows that the CO_2 concentration is very high between the two windows. However, being too close to an opening, it would not be an appropriate location for sensors. The same analysis method was applied to Case B1, C1 and D1 (images not shown due to space limit). The results show similar locations have been identified, mainly away from the windows of the office. Winter cases show much higher but more evenly distributed CO_2. Therefore, very few locations are identified for C1 and D1. Based on all result analyses, Figure 3 shows all the proposed locations for combined sensors in the case study office. Some existing sensors are already located at the appropriate places. For instance, the sensor at location 8 is necessary to respond to a change of occupancy and heat gains when a meeting is being held. The sensor at location 7 can detect the high air temperature that seems to be accumulating in the "R&D" corner. Only location 1 is identified in the "main office" as this part of the office usually has lower temperature or CO_2 than other areas. Locations 2 and 3 are sufficiently distant from occupants, heat sources and openings. The level of temperature and CO_2 in these areas are consistently high under different conditions. Locations 5 and 6 are often found to have high temperature or CO_2, due to the high occupancy in the "accounts" area.

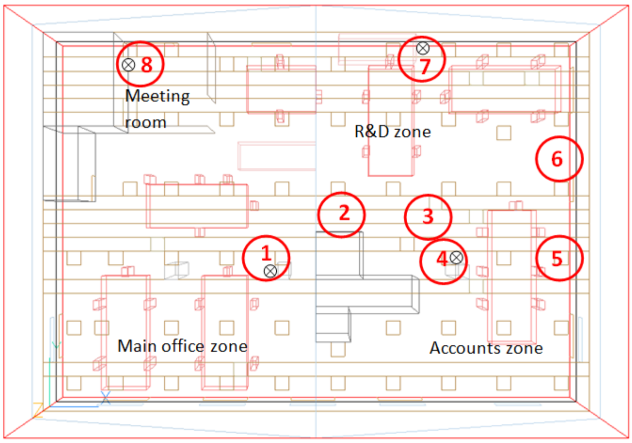

Figure 3 Case study office plan with recommended combined sensor locations

5 Discussions

The validation of CFD results was highly encouraging. For Case A1, there is a deviation of 0.64% between simulation result and measured values. 2.4% deviation for Case B1. For the winter case, the mean deviation from the measurement values is found to be 5.6%. The winter case shows a lower accuracy than the summer cases, because there are several uncertainties involved in the winter case. The heat output of radiators is an approximation. The model had one fixed opening and one roof vent open at 5% to simulate a fully closed office with infiltration, the position of the opening could have affected the temperature or CO_2 at the measurement area. In reality, the number of occupants can also vary from day to day, therefore a mean deviation may not be justified. Another compromise between accuracy and practicality is made for the mesh. Due to the large domain and a great number of internal objects, some accuracy has been sacrificed for time constraints.

It is also important to point out the limitations of the CFD model when discussing the simulation results. The CFD model has been built in the simplest form to simulate the air temperature, CO_2 distributions and flow patterns. Factors such as heat loss or heat gains through building fabrics, solar radiation, air movement between the building zones and the wind effects have been ignored. Each of these parameters could influence the indoor air temperature and CO_2 distribution; the model is undoubtedly less accurate without them.

6 Conclusions

This paper reports on the research that aimed to optimise the locations of combined sensors in open plan naturally ventilated offices. Based on the CFD model of an open plan office, temperature and CO_2 distributions have been found for four different operating scenarios. Eight optimal locations have been identified for the case study office. One is positioned in the "main office" area, one in the "meeting room", the other locations are found in the "R&D" and "accounts" areas where occupancy, temperature and CO_2 are generally higher. It should be noted that natural ventilation is a holistic concept, it cannot be achieved by either design, or controls alone. There are some building features in the case study office that counteract the natural ventilation. The staircase and elevator blocks in the centre of the open plan office seem to be the cause of the "accounts" and "R&D" areas having higher temperature in general and higher CO_2 concentration in most summer scenarios. Therefore, in open plan naturally ventilated offices, a clear ventilation path is important.

The optimisation of combined sensor locations in the case study office has given an insight to the possible locations in open plan naturally ventilated offices in general. Some key points to be considered are:

- Sensors should be placed at breathing height of approximately 1.1m, away from openings, doors, occupants and heat sources.
- A dedicated sensor in any separated spaces from the open plan office.
- The sensors should be mounted on columns facing away from the openings.
- Sensors could be located on the rear wall furthest away from the openings.
- A sensor should be placed in the area where the most of occupants are seated as the CO_2 tend to be higher.
- If there is any obstruction in the ventilation path, a sensor should be placed on the obstruction facing away from the opening, where the temperature and CO_2 are likely to be higher.
- An optimal location should consistently have high temperature and CO_2 concentration relative to other areas of the occupied space under different operating conditions.

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