Numerical investigation of indoor environmental conditions in an office

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ABSTRACT

The purpose of this work is to study numerically the indoor environmental conditions in an office. The indoor air quality status has already been studied experimentally under different indoor and outdoor conditions and it was found that indoor originated pollutants' concentrations (CO_2, PM_{10} and total VOCs) were elevated when smoking was taking place and the windows were kept closed. In order to investigate the mechanisms that affect the indoor environmental conditions and the indoor chemistry the CFD model PHOENICS and the Multi chamber Indoor Air Quality model (MIAQ), were applied based on input data obtained during the experimental campaign. The indoor velocity, temperature and inert pollutant fields established indicated low wind speeds and a relatively non-uniform flow field due to the existence of obstacles. Finally, MIAQ results indicate that deposition is an important factor that affects the indoor pollutants' levels.

1. INTRODUCTION

In the last decades indoor air quality has become a public health concern since people spend more than 80% of their time indoors. Studies have concentrated on the measurement of pollutants concentrations in indoor environments, such as residences, offices, shopping malls and restaurants, giving a comparison of their pollution status and identifying indoor pollutants sources (Lee et al., 2002). Computational Fluid Dynamics (CFD) codes have become an important tool in the research field of indoor air quality. They are currently applied for investigations of indoor airflow fields for building design and optimum ventilation purposes (Xing et al., 2001) and for pollutants dispersion in working areas for health and safety reasons (Cheong et al., 2003). Furthermore, in many cases the study of air quality is facilitated with the use of the microenvironment approach, which segregates the ambient air environment to large volumes of air with homogeneous pollutant concentration. It is assumed that the main contributions to the change rate of the indoor concentrations are outdoor pollution, the transport between the indoor and outdoor environments, the deposition on indoor surfaces and the chemical mechanisms (Smolik et al, 2005, Riley et al., 2002).
Within that frame the main objective of this work is to study numerically the indoor environmental conditions that prevail in an office while fully occupied under natural ventilation conditions with the aid of a CFD model and an indoor chemical model. The input data necessary for the applications were obtained during an extensive experimental campaign.

2. EXPERIMENTAL METHODOLOGY

The office is located on the first floor of the Applied Physics Department building at the University campus, which is in a suburban area not close to heavy traffic roads. The office is equipped with electronic computers, printers and furniture, while a wall to wall carpet is installed. It covers an area of 70 m^2 and is daily occupied by at least 7 people. Measurements were taken under different scenarios including occupation conditions, opening of windows, operation of the air conditioning system and smoking. For the needs of the current study the following measurements were taken:
Continuous measurements of PM_1, $PM_{2.5}$, PM_{10} indoor aerosol mass fractions with an environmental particle monitor (Osiris, Turkney Systems) at 1 minute intervals. For size sections: 0.3-0.5 μm, 0.5 – 1.0 μm, 1.0 – 2.5 μm, 2.5 – 5.0 μm and 5.0 – 10.0 μm.
Continuous measurements of the outdoor aerosol mass for the same size sections as above with a particle counter (Lighthouse Handheld 3016 Particle Counter) at 1 minute intervals.
Total VOCs and CO_2 measurements with two portable indoor air quality monitors (IAQRAE and ppbRAE of RAE systems).
Spot mean air velocity, temperature and turbulence intensity measurements at 1-min sets at the windows, the door and the office area with a DANTEC FlowMasters.
Surface temperature of indoor materials (walls, desks, cupboards etc.) with an infrared thermometer.

3. CFD MODEL – INITIAL AND BOUNDARY CONDITIONS

The PHOENICS CFD code (Version 3.5.1, 2003, CHAM Ltd.) solves the time-averaged conservation equations of mass, momentum, energy and chemical species in steady three-dimensional flows. The discretization of the domain is followed by the reduction of the previous equations to their finite domain form using the "hybrid formulation of the coefficients" and the solution technique employs the SIMPLEST algorithm. The standard k-ε turbulence model is applied, while buoyancy effects are considered. To improve convergence, under-relaxation was used.

A 3-D rectangular enclosure was considered in Cartesian coordinate system (Figure 1). The domain size is 7m x 10m x 3.5m and it includes 3 windows, 1 door, 7 desks, 11 partition walls, 2 tables, 6 cupboards and 1 refrigerator. The dimensions of the modelled objects are real and the domain geometry is as detailed as possible, taking into account computational efficiency. The boundary and initial conditions based on the experimental measurements are: (a) Fresh air comes in the office through the partly open windows and it is taken out of the office through the open door, (more details given in Table 1). The surface temperatures of indoor materials range between 22.5 and 27.7°C. (b) People are modelled as heat and scalar sources emitting metabolic CO_2. One student corresponds to one desk. The maximum CO_2 concentration based on measurements was found to be approximately 2346mgm^{-3} very close to each person (Figure 1).

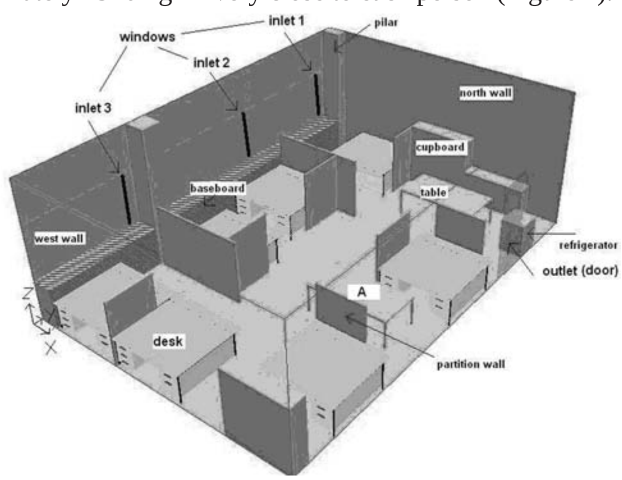

Figure 1. The computational domain.

Table 1. Experimentally measured air inlet data.

Air inlet	Measurement height (m)	Velocity (m/s)	Turbulence intensity (%)	Temperature (°C)
1	z=1.5	1.6	46	22.3
1	z=2	1.36	50	22.4
1	z=2.5	2.26	47	22.2
2	z=1.5	1.8	33	22.6
2	z=2	1.79	22	21.9
2	z=2.5	1.36	63	23.2
3	z=1.5	2.86	47	22.5
3	z=2	4.25	12	21.2
3	z=2.5	2.31	44	21.6

The cases studied are the following: a) Basic case: The office is empty, the door is open and the windows are partly open. Grid cells employed are 67x75x40 and the minimum cell size is 0.1x0.13x0.09m. b) Working-day case: The office is fully occupied (7 students) on a typical working day and ventilation conditions are the same as previously. Grid cells employed are 77x87x41 and the minimum cell size is 0.09x0.12x0.09m.

4. MIAQ MODEL INPUT CONDITIONS

The Multi chamber Indoor Air Quality model (MIAQ) is a mathematical model for both indoor aerosol dynamics and the concentrations of chemically reactive compounds in indoor air. MIAQ links a building and ventilation system structure characteristics to a mechanistically sound analysis of particle dynamics and indoor chemistry (Nazaroff and Cass, 1989). For the present work, an attempt is made to theoretically simulate the indoor aerosol dynamics. The necessary input data included the measured outdoor aerosol mass, the indoor temperature and relative humidity along with the temperature of the surfaces and the geometric characteristics of the indoor surfaces. Measurements of the indoor aerosol mass were used in order to compare them with computed results. Results are given at one hour intervals.

The simulated room was considered to be a single zone occupying a volume of 245 m^3. Indoor temperature ranged between 24.3 and 27 ºC, while the relative humidity values were between 20% and 35%. CO_2 concentrations ranged between 531 and 704 ppm. The ventilation rates were calculated following the methodology presented by Bartlett et al 2004. The methodology involves the solution of the mass-balance equation for the CO_2 concentrations, considering indoor homogeneity and negligible deposition. Outdoor CO_2 concentrations ranged on average at 1170mgm^{-3}. The indoor emission rate of CO_2 was considered mainly due to human respiration and was taken to be 0.3 L min^{-1} per person (Godwin et al, 2003). Thus, the ventilation rates ranged between 1 and 10 m^3 min^{-1}, depending on the pressure difference between the indoor and outdoor environment.

5. CFD MODEL RESULTS

Simulated results of the Basic case exhibited satisfactory agreement with measured data given that the flow is characterized by very low wind velocities. Table 2, gives the experimental and computed velocities (U_{exp} and U_{th}) and temperatures (T_{exp} and T_{th}) for several domain points.

Table 2. Experimental and theoretical velocities and temperatures at selected domain points for the Basic case.

Measurement location	U_{exp} (m/s)	T_{exp} (°C)	U_{th} (m/s)	T_{th} (°C)
baseboard of west wall	0.15	25.5	0.28	22.79
desk	0.36	23.8	0.05	22.95
cupboard	1.36	23.1	0.55	22.67
refrigerator	0.50	23.4	0.12	22.87
table	0.19	24.4	0.08	22.84
partition wall	0.23	26.3	0.25	22.86
outlet (at z=13cm)	0.29	24.6	0.44	22.89
outlet (at z=1.3m)	0.55	23.8	0.23	22.76
outlet (at z=2.27m)	0.77	24.1	0.40	22.81

The wind field established on the y-z plane (from the north wall to the south wall) is presented in figure 2. It can be seen that three distinct vortex-like patterns are established characterized by low velocities in the centre and areas of acceleration near the obstacles of the room. The flow between the two successive vortices (from the right) seems to be downwards. The flow established is quite different on the x-z plane (from the windows to the door), since it seems to be divided into two "layers", (figure 3). Above a height of approximately 1.5 m the air coming in from the windows reaches the opposite side of the room, while at lower heights distinct vortices are developed due to the existence of the furniture and other obstacles. The wind speed remains very low of the order of 0.5 m/s. It is interesting to observe the flow field established in the office at a height of 1.5m (on the x-y plane). It is clearly seen that the air coming in from the three windows, with a velocity of the order of 2 m/s reaches the other end of the room in one case, but from the two windows on the right it does not due to the presence of partition walls. On the left side of the room a distinct vortex structure is seen whose boundaries are set by the partition walls and the same at various locations in the room. Furthermore, a large part of the room close to the door is characterised by very weak and almost uniform flow, of the order of 0.2m/s, driven by the draught towards the door, (figure 4).

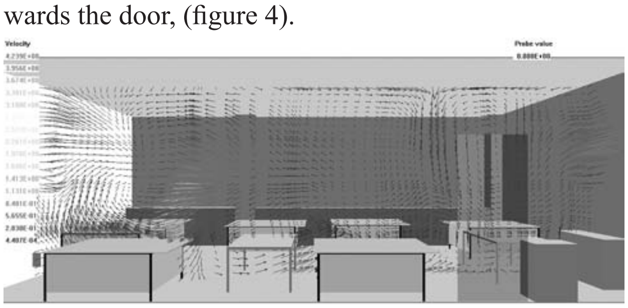

Figure 2. y-z plane view of the flow field (at x=5m).

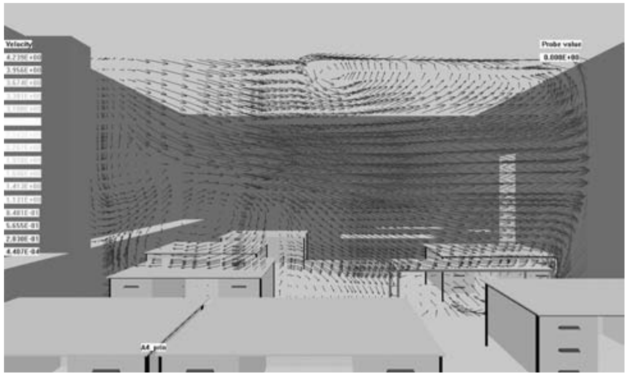

Figure 3. x-z plane view of the flow field (y=3.8m).

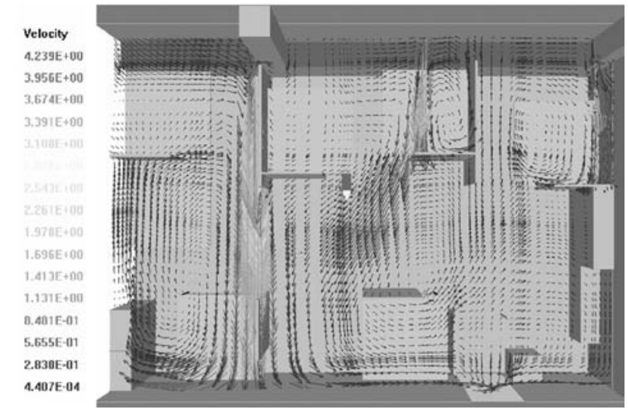

Figure 4. x-y plane view of the flow field (at z=1.5m).

The temperature field established does not present any distinct features besides the fact that air temperatures are higher close to objects and decrease moving away from them along the room, (figure 5). The room temperature is on average approximately 22.5 ºC.

Working day case: When the office is occupied by all 7 people working at their desks they are assumed to be motionless since this is a steady state case and hence their presence does not have an effect on the flow field developed, (not shown here).

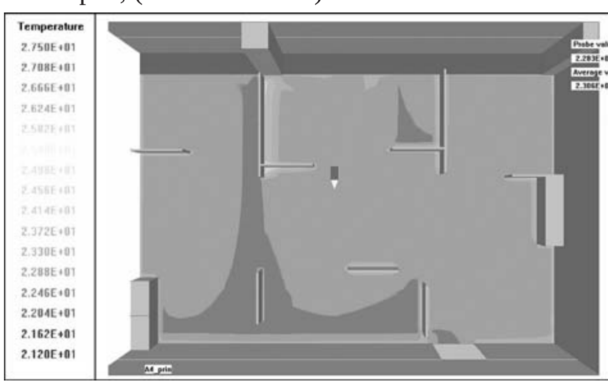

Figure 5. Plan view of the temperature field at z=1.5m.

However, regarding the temperature field computed by the model it can be seen that the presence of people consists of a heat source since the average room temperature has increased by about 1ºC. In figure 6, a plan view of the temperature field computed at a height of z=1m (approximately the height at which people work) is given. It is notable that the people working close to the windows (i.e., those within the distinct vortices formed between the partition walls) are the most important heat sources, the temperature close to them being approximately 27ºC and decreasing to the background value at a distance of 0.5 to 1m away from them depending on the air flow. At points of the domain where the flow is very weak (i.e., close to the door) the temperature contours originated by the people are not distinct.

Computed results of the CO_2 dispersion pattern are given in figure 7. As expected each person consists of a source emitting CO_2, which is then transported by the flow field developed in the room. The maximum CO_2 concentration found in the close vicinity of each person reaches 2346mgm^{-3}. Concentration contours indicate higher concentration levels at the left side of the office because of local trapping, giving values of the order of 1079mgm^{-3} which is close to the limit set for indoor air quality. Better conditions prevail at the centre and the right side of the room. The average concentration at z=1m is 798mgm^{-3}.

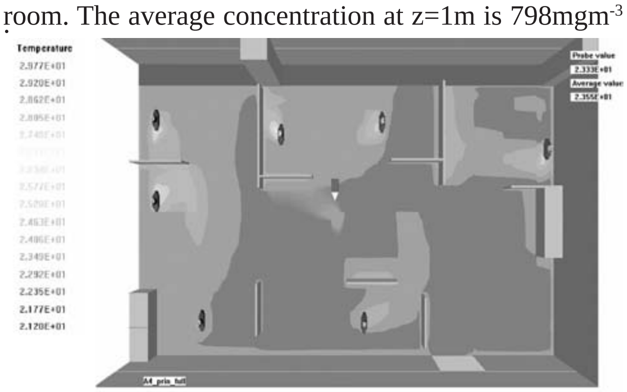

Figure 6. Plan view of the temperature field at z=1m.

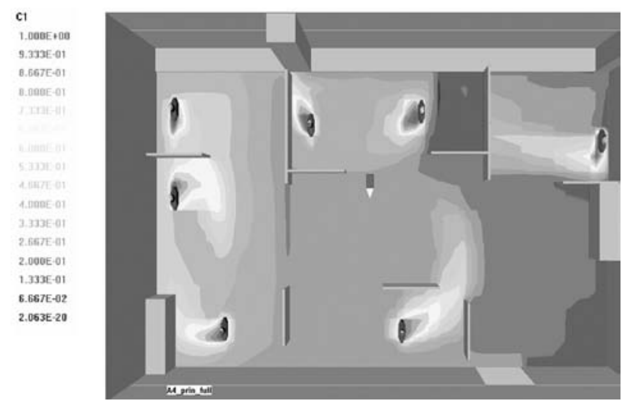

Figure 7. Plan view of CO_2 concentrations at a height of 1m (conc. C1 given as % relative to 2346mgm^{-3}).

6. MIAQ MODEL RESULTS

Figure 8 depicts the temporal evolution of the outdoor measured aerosol concentrations of the different size sections. As can be seen the lowest concentrations are observed for sizes larger than 10μm, mainly associated with dust, which range approximately between 0.5 and 2 μgm^{-3}. The highest values are found for aerosol sizes of 0.5-1.0 which range between 23 and 51 μgm^{-3} and originate from combustion emissions. In figure 9 a comparison of the indoor measured and computed concentrations for aerosol size sections of 0.3 – 1.0 μm is presented. As can be seen the model has slightly over predicted the measured values, however this difference is not considered significant. It is also interesting to not that indoor aerosol concentrations are lower than the respective outdoors for this size fraction, which indicates that they mainly originate from the outdoor environment. Comparison of measured versus computed values for a size section of 1.0 – 2.5 μm is quite satisfactory given that the modeled values follow the general trend of the measured ones, however perfect agreement can not be achieved since the measured data were limited and given at one minute intervals while the computed values are given at one hour intervals. Indoor and outdoor measured values are almost equal for this size section.

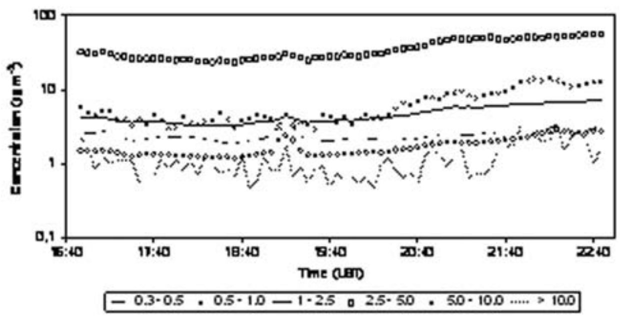

Figure 8. Temporal evolution of the outdoor measured concentrations of the different aerosol size sections.

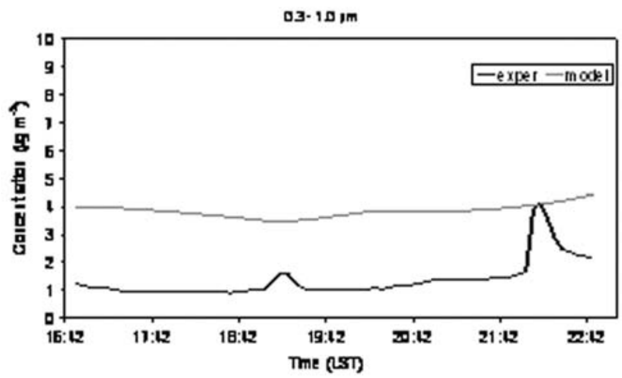

Figure 9. Temporal evolution of measured vs. computed concentrations for aerosol size sections 0.3-1.0 μm.

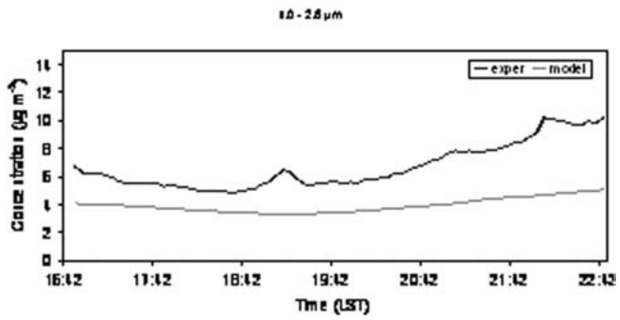

Figure 10. Temporal evolution of measured vs. computed concentrations for aerosol size sections 1.0 – 2.5 μm.

7. CONCLUDING REMARKS

The indoor environmental conditions that prevail in a naturally ventilated occupied office were studied numerically with the aid of a CFD model and an indoor chemical model. The input data necessary for the applications were obtained during an extensive experimental campaign. Preliminary results presented here revealed the following: a) Comparison of computed versus experimental results revealed that both numerical models performed in a satisfactory manner. b) The flow field and developed is characterised by areas of uniform flow and isolated vortices depending on the presence of objects (offices etc.), characterised by very low velocities. However, the presence of people does not seem to have an effect on the patterns established. c) People consist of an important source of pollution and heat. Intense contours of temperature and pollutant concentrations are formed around each person. Their dispersal is dominated by the general flow field, leading to areas of higher temperature and pollution. Regarding indoor CO_2 levels it seems that according to computational results the guideline limit is slightly exceeded. d) Concentrations of indoor and outdoor aerosol size fractions indicate that the finer aerosols are higher outdoors but the coarser are almost equal both in the indoor and outdoor environments. Further work is currently taking place in order to firstly include more ventilation and occupation/use scenarios for more CFD computations. Secondly, there is an ongoing experimental campaign in order to collect a larger data base of aerosols and other pollutants such as total VOCs and CO_2 which, will be averaged to hourly values. Thus, the MIAQ model will also provide computations of total VOCs concentrations as well as more chemical reactions.

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