The Use of Mass Balance-Based Model for Indoor Air Pollutant Concentration Modeling Problem

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Abstract:

Indoor air quality is very important for human health, comfort, performance and productivity since people spend more than 80% of their time indoor environments such as school, office, home and other building. Some pollutants are mostly at higher concentrations indoors than outdoors and can affect negatively human health and productivity. Therefore, correct prediction of indoor pollutant concentration will guide in making the necessary arrangements indoors in order to spend their time more efficiently.

In this study, we propose to estimate concentrations of CO_2 – a gaseous indoor air pollutant – based on a mathematical model. As an example, a building contains interconnected three rooms is modeled and pollutants' concentrations are calculated with respect to time using the multiple compartment mass balance based model. Outputs of the models which have different ventilation conditions depending on the total number of humans in the rooms are compared and the dispersions of indoor CO_2 levels are analyzed.

Key words: Airflow, carbon dioxide, indoor air quality, mass balance-based model, pollutant concentration

1. Introduction

More researches point out that the pollutants are in higher levels at indoor air than outdoors and so indoor air is usually dirtier than outdoor air [1, 2]. CO_2 is an important indoor air pollutant and the measurement of indoor CO_2 levels is one of the methods applied to control and evaluate the indoor air quality (IAQ). Although CO_2 is not alone an indoor air pollutant, the increase of CO_2 concentration indoor air indicates IAQ is starting to become bad. The indoor air concentration of CO_2 linearly increases with increasing the number of occupancies in the indoor environment and reduces ventilating the environment [1, 3].

In this study, an indoor air quality model based on the mass balance equation is used to estimate CO_2 (carbon dioxide) concentration levels of indoor air by indoor environment configuration (windows open, windows closed, air conditioned, etc.) and using the number of people.

In the first portion of the paper, the formulation of single compartment and multi compartment IAQ models are described, model parameters and their specification are mentioned. The next

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portion provides information on the applications of IAQ models and the software developed to predict CO_2 amounts and fourth portion presents the results of the simulation. The final portion of the paper summarizes and concludes the results.

2. Single and Multi Compartment IAQ Model Formulation

IAQ models are used to analyze the effects of sources and sinks indoors and to calculate indoor pollutant concentrations, to understand interactions of ventilation and indoor environment characteristics, and to control whether indoor air is good.

In this study, a multi compartment IAQ model is used to examine how CO_2 concentrations vary according to micro environment configuration and the number of occupancies.

General mass balance equation is given by Eq. (1).

$$\begin{matrix} mass\ at\ time \\ (t+\Delta t) \end{matrix} - \begin{matrix} mass \\ at\ time\ t \end{matrix} = \begin{matrix} entered\ mass \\ from\ t\ to\ \Delta t \end{matrix} + \begin{matrix} generated\ mass\ from \\ he\ sources \\ between\ t\ and\ \Delta t \end{matrix} - \begin{matrix} exited\ mass \\ from\ t\ to\ \Delta t \end{matrix} \quad (1)$$

For a single compartment *i* in multi compartment IAQ model, pollutant mass equation is written as follows:

$$V_i \frac{dC_i}{dt} = S_i - L_i C_i \quad (2)$$

where C_i is indoor pollutant concentration in compartment *i* (mg/m^3), t is time (s), V_i is the volume of compartment *i* (m^3), S_i describes the sum of generation rates of all sources ($mg\ s^{-1}/m^3$) and L_i is sum of loss rates due to all sinks (s^{-1}) within compartment *i* [4].

Pollutants are generated by indoor sources; enter a compartment through infiltration and supply air from ventilation system; are removed from indoor air by means of exfiltration, deposition to indoor surfaces and air flows from indoors to ventilation system; are exhausted outdoors due to ventilation system, and leaked from other compartment/s connected to the compartment and from the compartment connected to other ones [5]. These parameters effect the amounts of indoor air pollutant are mathematically expressed in Eq. (3) and Eq. (4).

$$S_i = \frac{1}{V_i}\left(C_{OA} P Q_{o,i} + \sum_{j=1}^{N} C_j Q_{j,i} + C_h Q_{h,i} + \sum_{s=0}^{M} G_{i,s}\right) \quad (3)$$

$$L_i = \frac{1}{V_i}\left(Q_{i,o} + \sum_{j=1}^{N} Q_{i,j} + Q_{i,h} + A_i v_d\right) \quad (4)$$

where C_{OA} is outdoor pollutant concentration (mg/m^3), P is penetration factor (the percentage of pollutant from the outdoor enters the indoor), $Q_{o,i}$ is volume air flow (infiltration rate) from outdoor to compartment *i* (m^3/s), $Q_{i,i}$ is volume air flow from compartment *j* to compartment *i* (m^3/s), N is the total number of compartments, C_h is pollutant concentration of HVAC (Heating, Ventilation, and Air Conditioning) system (mg/m^3), $Q_{h,i}$ is volume air flow from HVAC system to compartment *i* (m^3/s), v_d is deposition velocity (m/s), A_i is the surface area of compartment *i* (m^2), $G_{i,s}$ is the generation rate of source *s* in compartment *i* (mg/s) and M is the total number of indoor sources within compartment *i*. The index *o* refers the outdoor air and *h* the HVAC system.

To estimate the concentration of compartment *i*, analytical solution of the equation obtained when (3) and (4) equations is placed on Eq. (2) is used.

$$C_i = C_0 e^{-L_i t} + \frac{S_i}{L_i}(1 - e^{-L_i t}) \tag{5}$$

where C_0 is the initial pollutant concentration. The pollutant concentration of HVAC system can be computed using the following equation.

$$C_h = \frac{\sum_{j=0}^{N}(1-\eta)Q_{j,h}C_j}{\sum_{j=0}^{N}Q_{j,h}} \tag{6}$$

where includes filter efficiency η [4].

3. Model Structure

CO_2 is an odourless and colourless gas. The molecular weight of CO_2 is 44.01 g/mol. The most important source of CO_2 is breathing air of aerobic organisms. The outdoor concentration of CO_2 can vary between 350 (630 mg/m^3) and 400 ppm (720 mg/m^3) and indoor CO_2 concentration should be lower than 1000 ppm (1800 mg/m^3) – standard value proposed by ASHRAE – for acceptable indoor air quality [1, 6].

The levels of CO_2 indoors depends on the number of people, the size of room/building/facility/vehicle, the amount of fresh air entering the room from outdoor and the outdoor air concentration and the existence of combustion products [7]. CO_2 use balance equations such as moisture and other materials [8].

In this study, humans and their indoor behaviours are used as CO_2 sources. The rate of CO_2 emitted by people depends on their size and their physical activities. The amounts of CO_2 generation (emission rates) per person can vary depending on human activities as given in Table 1 [9, 10].

Table 1. The amount of CO_2 released into the air through human activities

Activity	(l/h)	kg/s
Sitting	15	0.00417
Making light work by hand	23	0.00639
Making work by hand or slow walking	30	0.00833
Making hard work by hand or fast walking	30	0.00833

The building applied to calculate the amount of CO_2 concentration has three rooms: A, B and C. The rooms are interconnected each other and have air flows between them as shown in Figure 1.

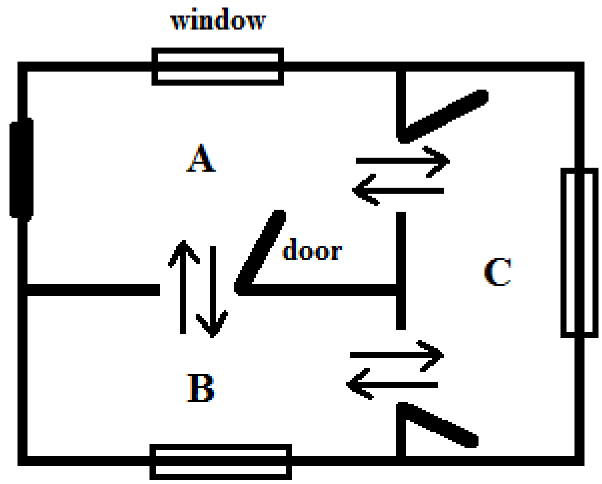

Figure 1. Schematic representation of the multi room building

All rooms in the building are well mixed, but the building as a whole cannot be well mixed, because indoor concentrations of the rooms may be different from each other. The geometrical dimensions of A, B and C rooms are 8 m × 5 m × 4 m, 8 m × 4 m × 4 m and 9 m × 4 m × 4 m, respectively. Each room contains one window (2.5 m in height and 1.2 m in width) and at least one door (2 m in height and 2 m in width).

Pollutant source (e.g. infiltration, pollutant generation of indoor source) and sink (e.g. exfiltration, recirculation, deposition to surfaces) terms for each room in the building according to the multi compartment IAQ model equations are illustrated as Figure 2. The rooms are linked to a common HVAC system and have air flows between each other rooms. The outdoor air is supplied through open windows/doors and the HVAC system (envelope leakages are ignored). HVAC provide filtered outdoor air (mixed with return air) to maintain comfort conditions of the building.

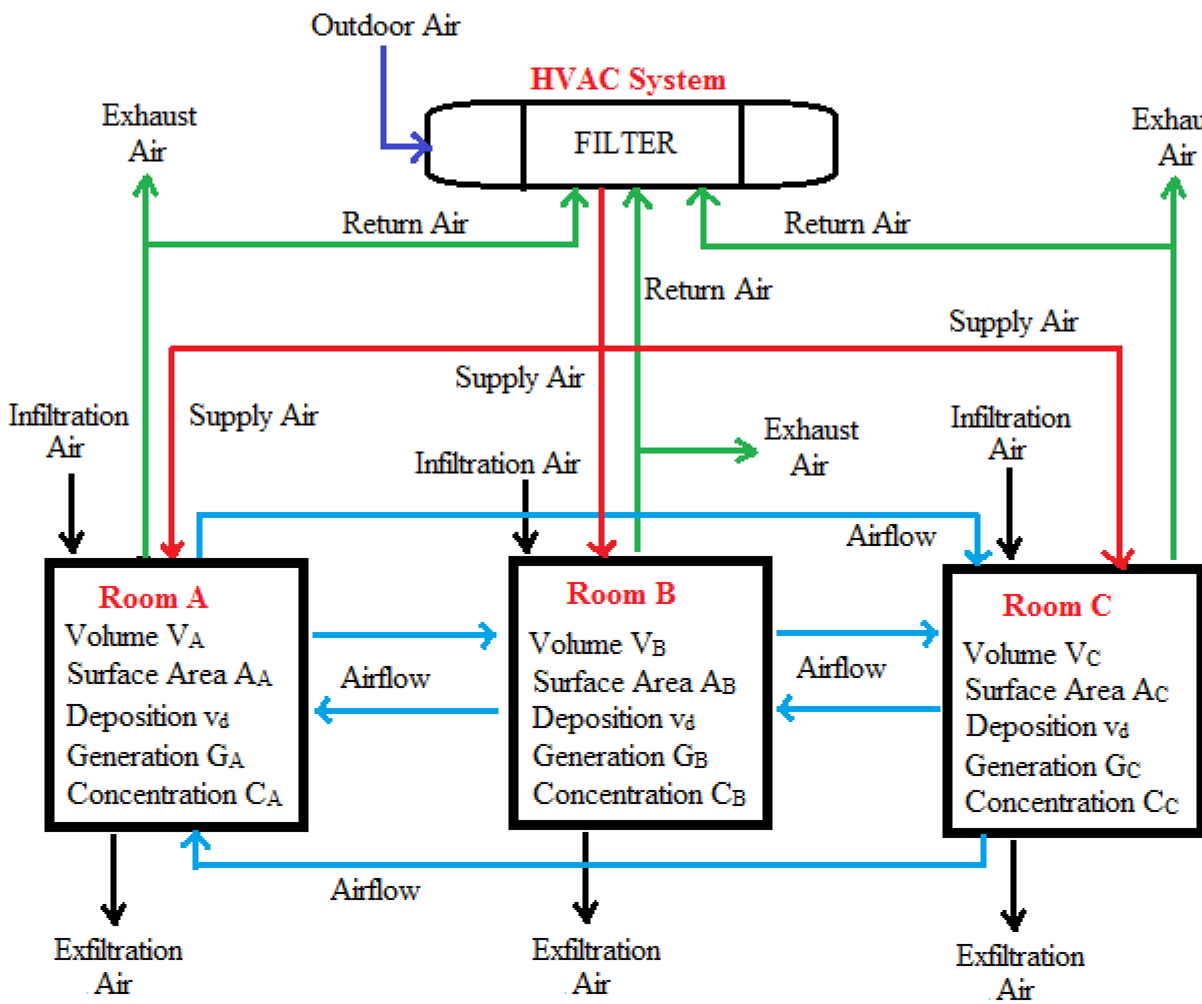

Figure 2. Schematic diagram of sources and sinks indoor environment

In this study, a special software which has a user interface as shown in Figure 3 is developed to predict the values of CO_2 concentrations in the rooms depending on air exchange rates between the rooms, differences in room configuration, indoor/outdoor CO_2 concentrations, the total number of humans in Room A and other indoor properties. Infiltration, exfiltration, room-to-room air flow rates and air change rates between the rooms and outdoor are model inputs as constant air flows and are not calculated using pressure and temperature values of indoor environment.

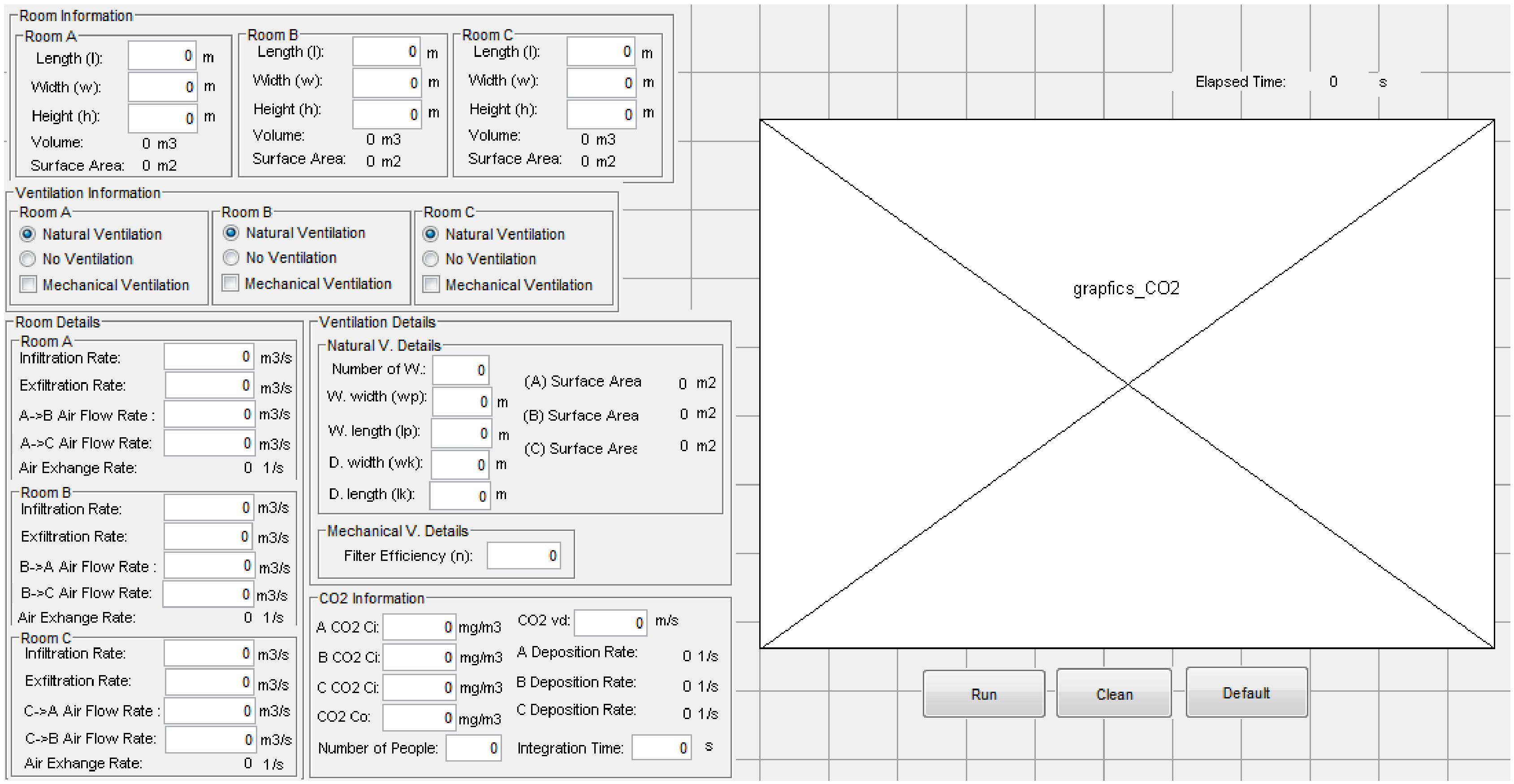

Figure 3. User interface of indoor air quality modelling software

The initial indoor CO_2 concentrations in rooms A, B and C are 700, 800 and 1000 mg/m^3, respectively. The deposition velocity of CO_2 is 0.003 m/s [11, 12]. The number of people who is making light work by hand is used to calculate CO_2 generation rate by the values in Table 1. The penetration factor is selected as 0.18 when ventilation is open and 0.16 when ventilation is closed.

Integration time for all computations is assumed 1 hour. HVAC and exhaust fans operate on this time interval. There is one person in Room A for CO_2 source. The indoor CO_2 concentrations are calculated according to the changing of ventilation conditions such only natural ventilation (doors and windows opening), only HVAC system (doors and windows closing), both natural and mechanical ventilation, and without any air exchange.

4. Simulation Results

The rate of CO_2 released into the air per person is assumed to be constant and the amounts of CO_2 generated by people are assumed to be linear with respect to the number of people in the room, has no other generation of CO_2.

CO_2 concentrations in unventilated rooms, natural ventilated rooms, ventilated by HVAC system and windows and ventilated by only HVAC system are presented as a function of time in Figure 4, Figure 5, Figure 6 and Figure 7, respectively. In these rooms, there are 1 and 10 people as CO_2 sources, respectively.

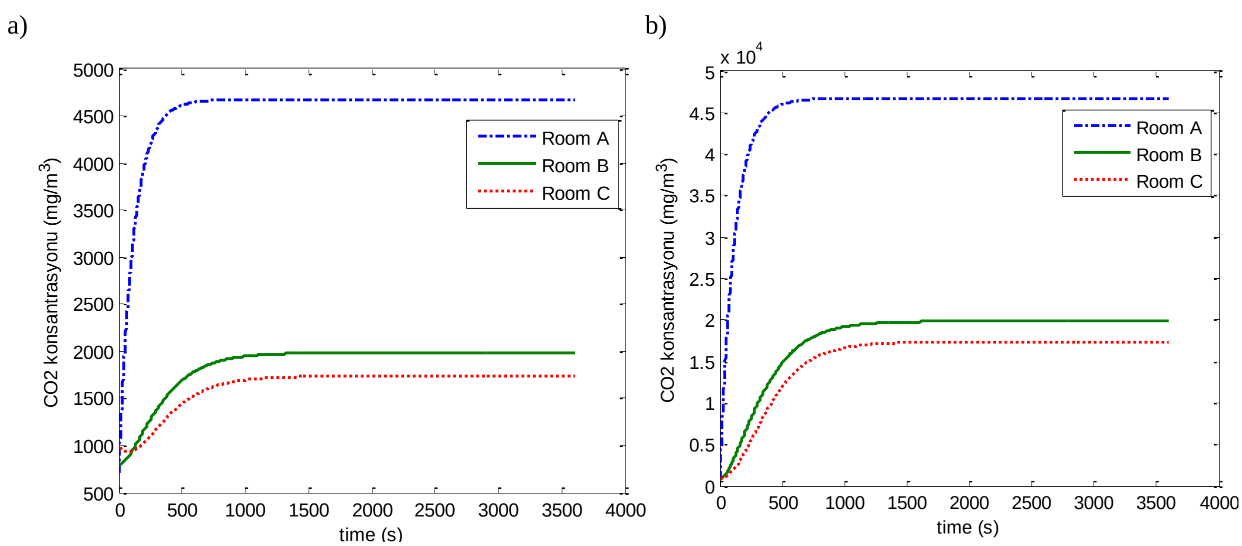

Figure 4. In unvented rooms located a) 1 person b) 10 people

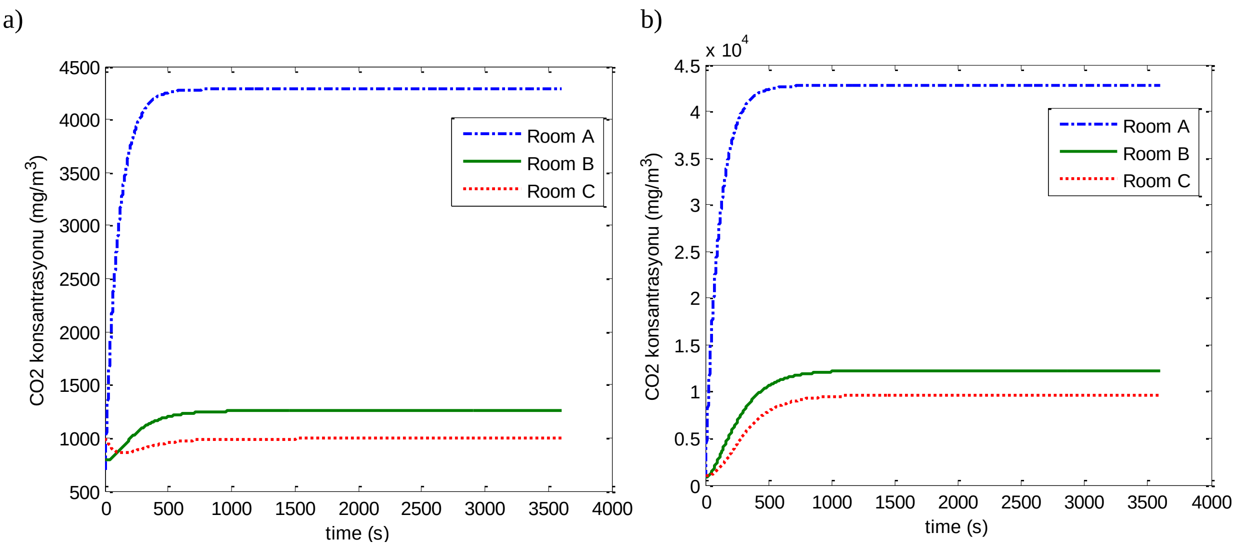

Figure 5. In naturally ventilated rooms located a) 1 person b) 10 people

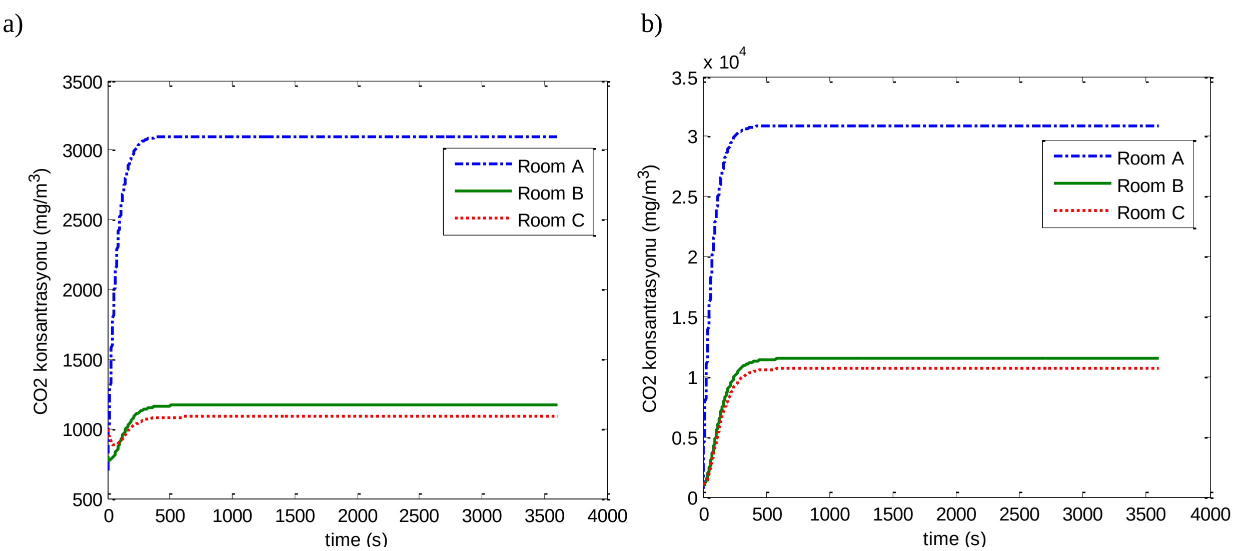

Figure 6. In the rooms ventilated, by HVAC system and through windows, located a) 1 person b) 10 people

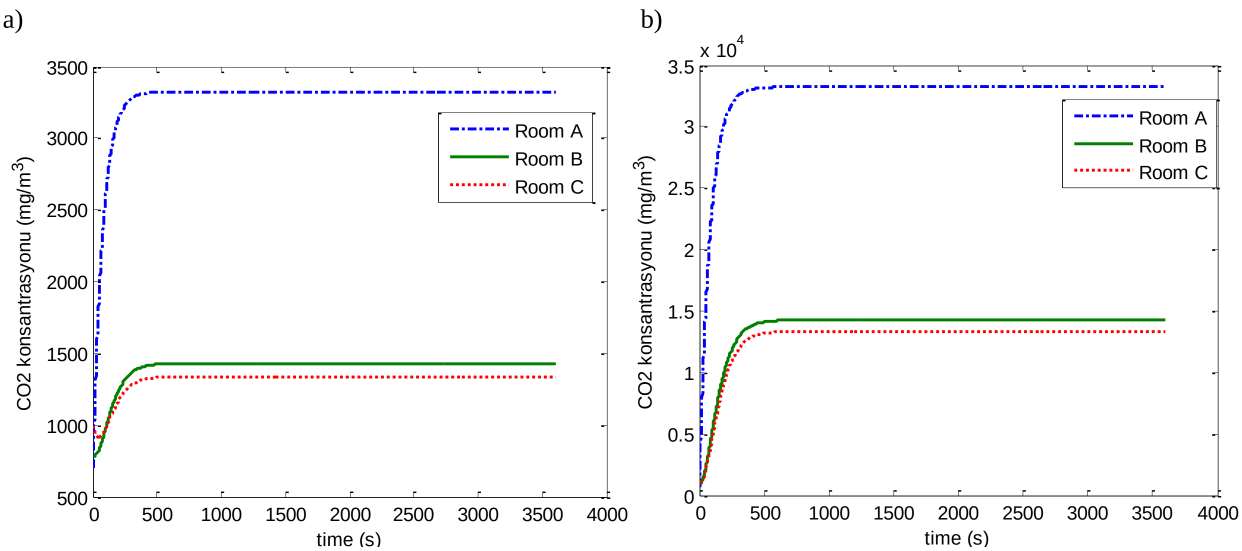

Figure 7. In the rooms, ventilated by only HVAC system, located a) 1 person b) 10 people

Acceptable limits for CO_2: the threshold limit value (time – weighted average 40 h per work week) is 9000 mg/m^3 (5000 ppm) and short term exposure limit (15 min) is 54000 mg/m^3 (30000 ppm) [13, 14]. The CO_2 concentration in each room is under the threshold limits as shown in the following graphics because of sufficient ventilation, air flows between the rooms (through open doors) and the small number of people.

The concentration of CO_2 increases depending on the number of occupants in the indoor environment. Also the amounts of CO_2 gaseous are at high levels in unventilated rooms and vented rooms ventilated by either or both mechanical and natural ventilation have lower pollutant levels than other rooms.

Conclusions

In this study, the models are developed for each room with mechanically ventilated (continuously), natural ventilated and unventilated scenarios in a multi room building. The developed models are simulated to estimate the amounts of CO_2 in each room at any second from the start to the end of operation time. The simulation results indicate that the amount of CO_2 in the indoor environment is changed according to ventilation configuration and increased depending on the number of occupants.

The models expressed in this study can be adapted for other indoor air pollutant species and used to predict exposures to indoor air pollution in the indoor environment. In addition, ventilation requirements can be determined by the model results.

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