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ORIGINAL PAPER

Modelling Accumulation of Respiratory-CO_2 in Closed Rooms Leading to Decision-Making on Room Occupancy

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Abstract: A model predicting time required to attain undesired levels of respiratory-CO_2 in closed rooms is described. The model works under the following assumptions: (1) room air is well-mixed, (2) indoor CO_2 does not exchange with outdoor CO_2, (3) there is no effect of individual occupants on CO_2 exhalation rate of other occupants, (4) there is no indoor CO_2 sink and all exhaled CO_2 end up increasing CO_2 concentration in the room, (5) apart from respiration, there is no other source of indoor CO_2, (6) breathing rates of occupants are constant throughout the period of occupation of room. The model makes use of anthropocentric parameters like body weight, height, du bois surface area, MET levels, etc., to calculate dedicated individual CO_2 exhalation rate and uses room volume and number of occupants to predict time required to reach user-earmarked levels of CO_2. A model run showed that in a closed room of $12 \times 12 \times 10$ m^3, respiration by one person at rest (65 kg body weight, 1.7 m height, basal respiratory quotient of 0.83) would take 4.37 h to reach 2000 ppmV indoor CO_2 when background indoor CO_2 level was 380 ppmV. This model would help allocating desired number of occupants in closed rooms to help avoid building up of undesirable levels of CO_2 in poorly ventilated offices, schools, hospitals or households that might frequently experience high levels of indoor CO_2, undermining health and performance of occupants, patients and workers.

Keywords: Activity level; Air quality; Du-Bois surface area; Exhalation; Indoor air; Occupational health

1. Introduction

Indoor CO_2 concentration can range from an equivalent level of background outdoor concentration (about 400 ppmV) to many thousands of ppmV, depending on the prevailing CO_2 generating activity indoors [1]. In the absence of a combustion source, indoor CO_2 build-up from human respiration relates to room occupancy, body height, weight, activity level and metabolic rate of occupants [2]. Erickson et al. [3] defined 'occupancy' as total number of people present in a defined part of a building. Occupancy measurements have been done through direct techniques like use of camera, passive IR sensors, ultrasonic sensors, motion detection sensors, CO_2 sensors etc. [4]. Human respiration itself could lead to attainment of 3000 ppmV CO_2 in indoor areas and indoor appliances like kerosene stoves, cooking gases, etc., could aggravate it further (National Collaborating Centre for Environmental Health, http://www.ncceh.ca/documents/practice-scenario/carbon-dioxide-indoor-air). Other crucial factors influencing CO_2 accumulation in closed rooms are room volume and air exchange rate, and as the later decreases, concentration of pollutants originated indoors increases along with an increase in residence time of indoor airborne pollutants [5].

Indoor CO_2 above a prescribed level can cause breathing disruption (increased breathing rate, acid–base imbalance and acidification of blood, disruption in calcium metabolism in bones) and problems like headache, nausea, vomiting, itching and burning in the respiratory tract, mucosal irritation, fatigue, slower work performance and increased absence from work [6–9]. Kajtar et al. [10, 11] has reported that controlled human exposure to CO_2 between 2000 and 5000 ppmV with ventilation rates unchanged had subtle adverse impacts on proofreading of text in some trials. Satish et al. [12] reported that at 2500 ppmV CO_2, large

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*Corresponding author, E-mail: d_majumdar@neeri.res.in and statistically significant reduction occurred in seven scales of decision-making. They concluded that direct adverse effects of CO_2 on human performance may be economically important and may limit energy-saving reductions in outdoor air ventilation per person in buildings. ACGIH [13] have recommended maximum occupational exposure limit for an 8-h workday of 5000 ppmV as a time-weighted average. American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 62.1 [14] recommends maintenance of a steady-state CO_2 concentration of 700 ppmV above ambient levels in classrooms to ensure provision of 7.5 l/s-person and control of body odour build-up. In Europe, EN13779 [15] classifies indoor air quality into high, medium, moderate and low quality that correspond to values of 250 ppmV, 500 ppmV, 800 ppmV, and 1200 ppmV indoor CO_2, respectively, above the ambient. The Netherlands Standard 1089 stipulates 5.5 l/s-person ventilation and a guideline peak value of CO_2 at 1200 ppmV [16], while Swedish standards require 8 l/s-person and an internal CO_2 concentration below 1000 ppmV [17]. In UK, Building Bulletin 101 (BB101) [18] uses CO_2 as an indoor air quality (IAQ) indicator for schools and goes on to prescribe a maximum concentration of 5000 ppmV and a mean occupied concentration of 1500 ppmV. Institute of Environmental Epidemiology [19] under Ministry of the Environment in Singapore specifies that indoor CO_2 level should not be more than 1000 ppmV on 8-h averaging time. These go on to show that CO_2 has been treated as an important indoor air quality parameter in many countries and needs to be managed judiciously to optimise office performance and improve human health.

Closed ill-ventilated rooms are not uncommon; people live in congested and unventilated urban shanties in many cities, jail inmates are kept in ill-ventilated cells, people work in closed air-conditioned offices with extremely poor ventilation or non-air conditioned closed office rooms in extreme winter. In India, such conditions are frequently encountered in poorly ventilated urban slums and households housing large families and crammed poorly ventilated office and school spaces [20–22]. Numerical modelling on occupancy-linked time-series CO_2 accumulation in closed rooms could be used as a decision-making tool to estimate time required for a specific number of occupants to force indoor CO_2 concentration reach undesirable levels. Thereby, we could fix the number of occupants in closed rooms or workplaces without reaching unsafe indoor CO_2 levels, improving efficiency at workplace and health of residents. Principally, occupancy of rooms could be straightaway fixed depending on space, privacy, cost, social acceptability and perception as to what could be a possible sitting or working arrangement, rather than depending on a crucial consideration like how quickly the room would reach undesirable CO_2 levels, affecting performance. Worldwide, high occupancy and even overcrowding are witnessed in non-residential buildings like offices, schools and prisons [23–25], leading to declining work performance from indoor CO_2 build-up. We propose a model for predicting indoor CO_2 accumulation linked to the number of occupants with a hypothesis that time taken for indoor CO_2 to reach a specific level in closed rooms can be reliably predicted, and therefrom, occupancy level could be conveniently fixed on case to case basis to avoid undesirable indoor CO_2 build-up.

2. Methodology

2.1. Model Description

Input variables required for the model to predict time needed to attain a target CO_2 level under definite human occupancy levels are: (1) background CO_2 conc., (2) target CO_2 conc., (3) room volume, (4) human Respiratory quotient, (5) activity level represented by MET value (i.e. metabolic rate per unit of surface area), (6) Du bois surface area of occupants and (7) human O_2 consumption rate. Target CO_2 level could be any indoor CO_2 guideline concentration value prescribed by regulatory organisations or any other level the user might desire to use as a benchmark, while background CO_2 may be assumed to be anything between 380 and 400 ppmV as commonly found in open-air ambience. The input variables were selected to take into purview (1) required elevation in indoor CO_2 level *vis a vis* room volume to trace the rate of change in indoor CO_2 concentration over time during room occupation, (2) generation rate of respiratory CO_2 linked to human factors and activity levels. The proposed model presents a series of calculations to calculate time (in hour) required to attain the target indoor CO_2 (ppmV) generated by human occupants who are known to produce CO_2 at a rate depending on their oxygen consumption rate, respiratory quotient, level of physical activity and Du-Bois surface area, which is governed by body height and body mass [26, 27]. Anthropocentric variables like body height and weight, metabolic activity and respiratory quotient are critical to calculate dedicated CO_2 generation rate of individuals, while other independent variables like room height, width and length towards room volume calculation are also important to estimate time required to attain target indoor CO_2 levels. When time required to reach undesired target indoor CO_2 level under certain room occupancy level is higher than expected time of room occupation, there would be no need to change room occupancy as under such occupancy level, the room would never experience undesired CO_2 levels and related performance drops or health complications. The physical representation of the model is presented in Fig. 1. Model boundary conditions are as below:

1. Indoor CO_2 does not get exchanged with outdoor CO_2
2. There is no other source of CO_2 in the room other than respiration by the occupants
3. There is no CO_2 sink indoors and therefore, all exhaled CO_2 is instrumental in increasing CO_2 concentration of the room
4. There is no effect of CO_2 exhalation of an individual occupant on CO_2 exhalation by others
5. The room air is well-mixed, resulting in homogenous mixing of exhaled CO_2
6. Breathing rate and tidal volume of occupants are constant during room occupation

The model incorporates CO_2 exhalation rate of individuals based on their body mass, height and corresponding body surface area, O_2 consumption, human respiratory quotient [28, 29] and goes on to calculate time needed to reach the target CO_2 level in a closed room of specific dimensions. The CO_2 generation rate (by respiration) of an individual is calculated by Eq. (1):

$$G = V_{O_2} \times \mathrm{RQ} \tag{1}$$

where G = CO_2 generation rate by respiration (L s^{-1}); V_{O_2} = rate of oxygen consumption (L s^{-1}); RQ= respiratory quotient, i.e. relative volumetric rates of CO_2 produced to O_2 consumed. The value of RQ depends on diet, level of physical activity and physical condition of the person in question [2, 26, 27]. For the proposed model, basal RQ rate of 0.83 has been used as a blanket value.

Rate of oxygen consumption V_{O_2} can be calculated by the following equation [28]:

$$V_{O_2} = (0.00276 \times \mathrm{AD} \times M)/[(0.23 \times \mathrm{RQ}) + 0.77] \tag{2}$$

where M = level of physical activity or the metabolic rate per unit of surface area, in METs (dimensionless) (Table 1); RQ= respiratory quotient (dimensionless); AD= Du Bois surface area (m^2) given by:

$$\mathrm{AD} = 0.203 \times H^{0.725} \times W^{0.425} \quad \text{(Emmerich and Persily 2001)} \tag{3}$$

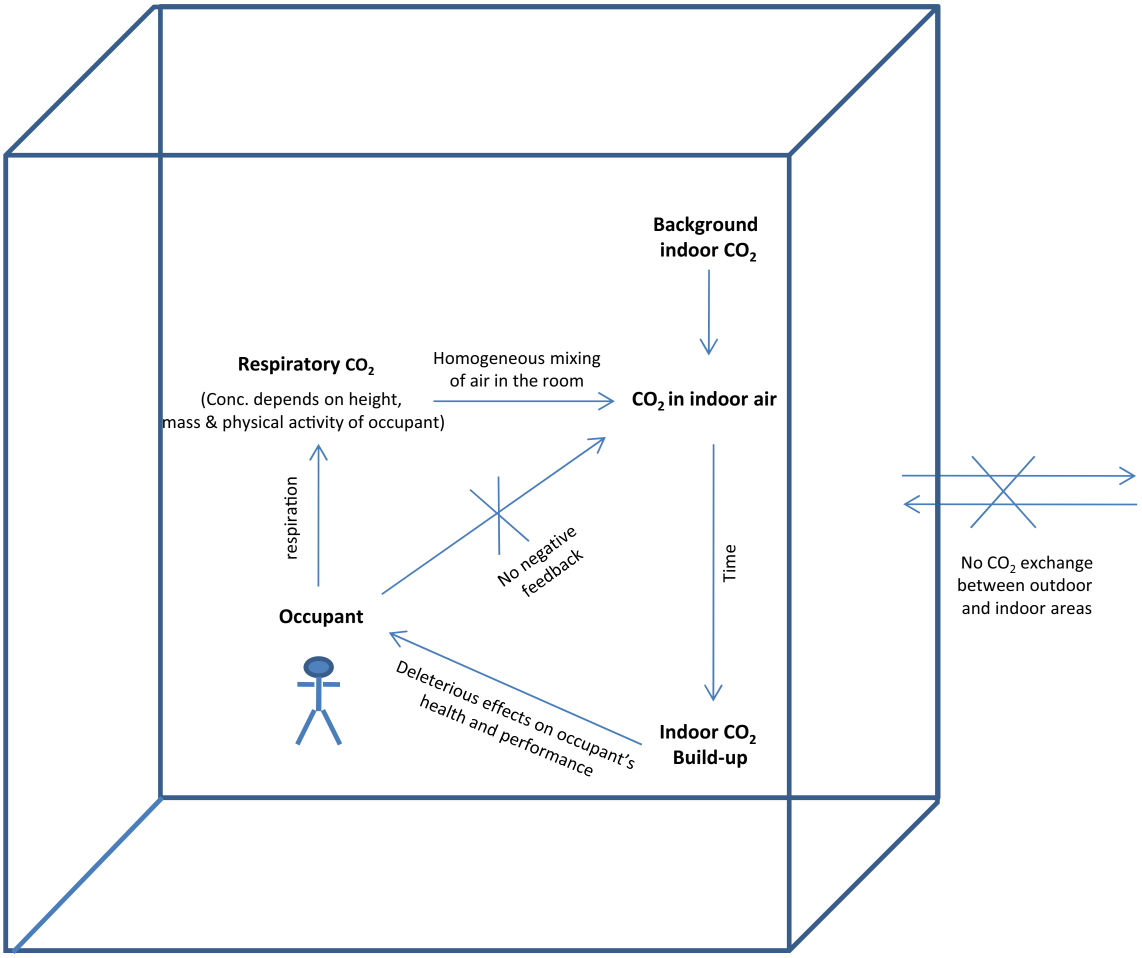

Fig. 1 Physical representation of the model

Table 1 Typical MET levels for various common activities

Activity	MET
Seated, quiet	1
Reading and writing, seated	1
Walking at 0.9 m s^{-1}	2
House cleaning	2–3
Exercise	3–4

Kulshreshtha and Khare [29]

where H = height (m); W = body mass (kg).

CO_2 generation rate of an individual occupant (G) can be multiplied by number of occupants to get total CO_2 generation for all occupants (G_{tot} in Eq. 4) in case the occupants share same body height, mass and MET level. In cases of occupants with different body height, mass and MET levels, as expected more frequently, G_{tot} needs to be calculated by summing up individual G levels. The Resting Metabolic Rate is considered to be 1 MET, which is defined as 58.2 W m^{-2} (18.4 Btu h^{-1} ft^{-2}) and equal to the rate of energy produced per unit surface area of an average person seated at rest [30]. The following formula is proposed for calculating time (in hour) to reach a target indoor CO_2 concentration:

$$t = \left[\left((d - i) \times a \times b \times c \times 28.32\right)/\left(G_{tot} \times 10^6 \times 60\right)\right]/60 \quad (4)$$

where t = time (h) to reach a target indoor CO_2 concentration; d = target CO_2 concentration (ppmV or μl l^{-1}) as chosen by the user; i = background zero-time CO_2 conc. in the room (ppmV or μl l^{-1}) [zero time is $t = 0$, or time from when CO_2 accumulation due to respiration actually starts]; a = length of the room (ft); b = width of the room (ft); c = height of the room (ft)

$$G_{tot} = \sum_{i=1}^{n} (V_{O_2} \times RQ) \quad (5)$$

[i = ith individual, $V_{O_{2i}}$ is O_2 consumption rate by the ith individual and G_{tot} is the total CO_2 generation rate by all occupants in L s^{-1}, RQ is respiratory quotient].

Constant 28.32 is used to convert room volume in ft^3 to litre (l); 10^6 for converting CO_2 generation rate in L s^{-1} to μL s^{-1}; 60 as a multiplier to convert μL s^{-1} to μL min^{-1} and then again as a denominator to convert the final result (t) from minutes to hour (h). The model algorithm is presented in Fig. 2.

2.2. Sensitivity Analysis

Sensitivity analysis of the model was undertaken by 'One at a Time' (OAT) technique that involved changing values, within commonly expected limits, of any one input variable at a time, keeping all other input variables unchanged and observing the extent of change in output, i.e. time (in h) taken to reach the target CO_2 level. Most commonly encountered range of values of anthropocentric measurements (height, weight, MET values), background CO_2 level and various preset target CO_2 levels were used for sensitivity analysis. Further, regression analysis of variable outputs obtained with changing input parameters like room length, room breadth, occupant's body mass and height, background CO_2 and target CO_2 concentration were undertaken to understand relationships between outputs and independent input variables.

2.3. Validation of Model Outputs

The model predicted outputs were validated by real-life experimentation in a closed rooms of different dimensions with different individuals who spent varying periods in such closed rooms, and time-series indoor CO_2 accumulation was monitored by a NDIR-based CO_2 m (SD800, Extech, Taiwan). This instrument with 1 ppm resolution had accuracy levels of ± 40 ppmV CO_2 at $\leq$ 1000 ppmV, ± 5% of CO_2 readings at $>$ 1000 to $\leq$ 3000 ppmV and ± 250 ppmV CO_2 at $>$ 3000 ppmV tested at 50 °C, as per 'Test Certificate' of Extech Instruments, Taiwan. Absolute measurement uncertainty was +5.4 ppmV, derived from 10 measurements of 649.1 ppmV certified standard CO_2 in balance N_2 (± 1% certification accuracy and ± 10% preparation tolerance; Alchemie Gases and Chemicals Pvt. Ltd.) with traceability to National Physical Laboratory, India (standard mixture prepared by gravimetric method, weight traceable to NPL). The relative measurement uncertainty was found to be 0.82%. The test rooms varied from 12 ft × 8 ft × 9 ft to 12 ft × 14 ft × 10 ft (H × L × W) size, and 1–2 test individuals occupied the rooms for about 2.1–4.5 h for a series of experimentation. Target CO_2 concentration was kept at 600–800 ppmV. The test individuals shifted positions every quarter of an hour to negate the bias of respiratory CO_2 release at one single point. The individuals were made to stay in closed rooms until attainment of various levels of indoor CO_2. Room air was mixed by ceiling and pedestal fans together at maximum respective speeds. Room temperature and RH varied between 25–28 °C and 52–61%, respectively, during this experimentation.

3. Results and Discussions

The model was test ran with *real-world* datasets based on individuals' anthropocentric data and room dimensions available in senior author's own institute. The model

Fig. 2 Model algorithm

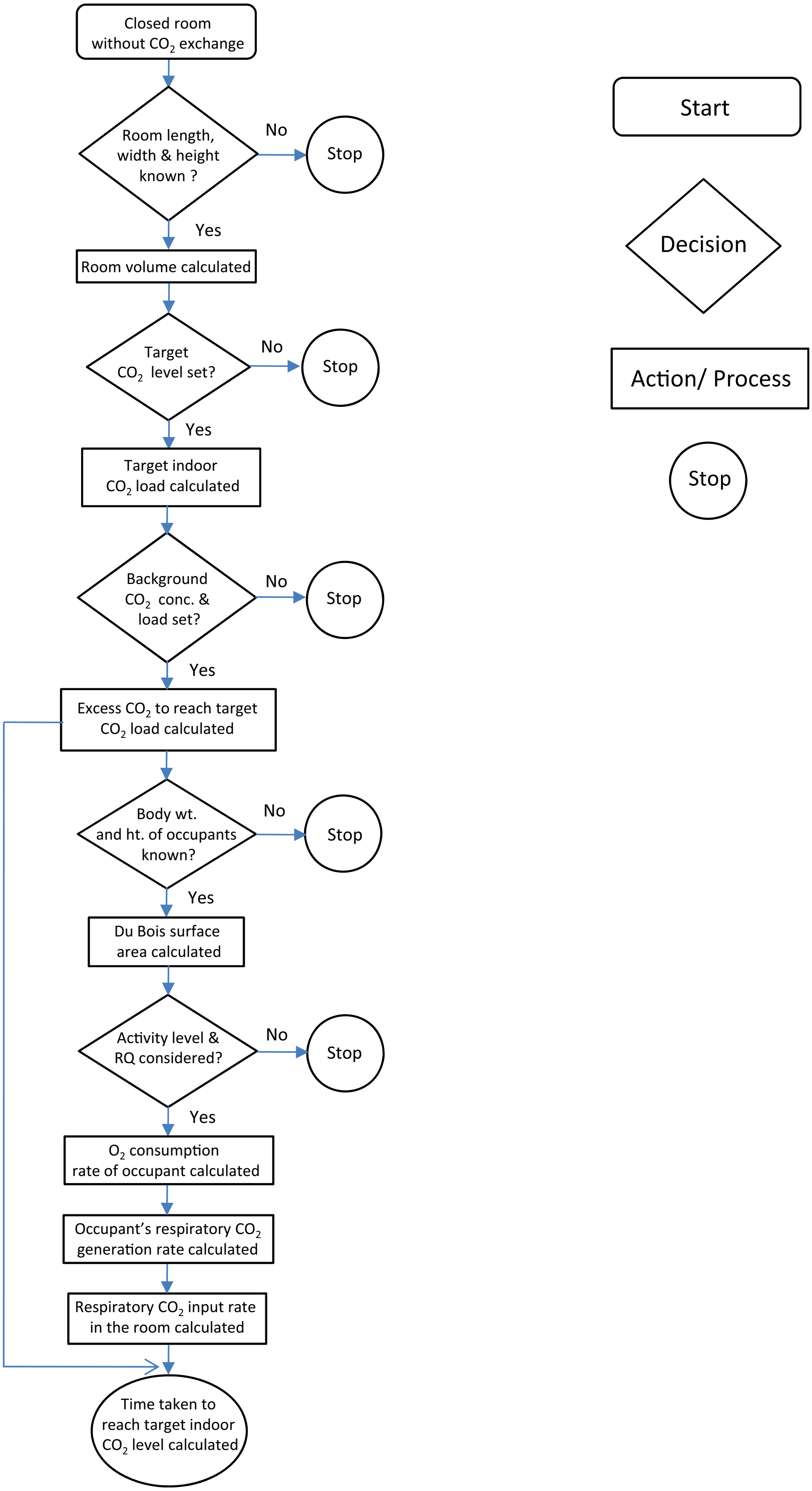

Table 2 Calculation of time required to reach target 2000 ppm[a] indoor CO_2 level via respiration of occupants of definite anthropocentric characters (two scenarios presented) occupying a closed room of certain dimensions

Input code	Input parameters/calculated parameters[b]	Unit	Formula[c]	Scenario-1 (One occupant 'at rest')	Scenario-2 (Two occupants, one 'at rest' and another 'walking')	
				Input/calculated value	Input/calculated value	
					Person 1	Person 2
A	Length of the occupied room	ft	–	12	12	12
B	Width of the occupied room	ft	–	12	12	12
C	Height of the occupied room	ft	–	10	10	10
D	Volume of the room	L	A × B × C × 28.32	40,780.8	40,780.8	40,780.8
E	Background CO_2 conc. in air (indoor), i	ppmV or $\mu L\ L^{-1}$	–	380	380	380
F	Background CO_2 load in air (indoor)	µg	E × D × $(44/22.4)^{d}$	30,439,954.3	30,439,954.3	30,439,954.3
G	Target concentration (indoor), d	ppmV or $\mu L\ L^{-1}$	–	2000[a]	2000	2000
H	Target CO_2 mass load (indoor)	µg	G × D × $(44/22.4)^{d}$	160,210,285.7	160,210,285.7	160,210,285.7
I	Excess CO_2 needed to reach target level (indoor)	µg	H–F	129,770,331.4	129,770,331.4	129,770,331.4
J	Body ht, H	m	–	1.7	1.7	1.9[e]
K	Body mass, W	kg	–	65	65	78[e]
L	Du Bois surface area, AD	m^2	$0.203 \times J^{0.725} \times K^{0.425}$	1.76	1.76	2.06[e]
M	MET (as per table), M	No unit	–	1	1	2[e]
N	Respiratory quotient, RQ (Basal)	No unit	–	0.83	0.83	0.83
O	Rate of O_2 consumption, V_{O_2}	$L\ s^{-1}$	$(0.00276 \times L \times M)/((0.23 \times N) + 0.77)$	0.005	0.005	0.0118
P	CO_2 generation rate (individual), G	$L\ s^{-1}$	N × O	0.0042	0.0042	0.0098
Q	No. of persons	Number	–	1	1	1
R	CO_2 input in room (indoor)	$L\ s^{-1}$	P × Q	0.004191	0.004191 ($R1$)	0.009819 ($R2$)
S	CO_2 input in room (indoor)	$\mu L\ s^{-1}$	$R \times 10^6$	4191.5	14,010.59 $[(R1 + R2) \times 10^6]$	
T	CO_2 input in room (indoor)	$\mu L\ min^{-1}$	S × 60	251,489.5	840,635.39	
U	CO_2 input in room (indoor)	$\mu g\ min^{-1}$	T × $(44/22.4)^{d}$	493,997.3	1,651,248.10	
V	Time required to reach target CO_2 conc. (indoor)	min	I/U	262.7	78.6	
X	Time required to reach to target CO_2 conc. (indoor)	h	V/60	4.38	1.31	

[a] Subtle adverse impacts on proofreading of text starts at this concentration [10, 11]; As per Wisconsin Department of Health Services (https://www.dhs.wisconsin.gov/chemical/carbondioxide.htm), indoor CO_2 levels of 2000–5000 ppm could lead to headache, sleepiness and stagnant, stale, stuffy air. Poor concentration, loss of attention, increased heart rate and slight nausea may also be present

[b] Symbols in column 2 are of formula 1 and 2, do not have any bearing on the formula presented in column 4

[c] The formulae are based on input codes listed in column 1

[d] Since 22.4 litre of a gas equals 1 mol of that gas

[e] Differentiating characters of the 2nd person

predicted theoretical time required (in h) to reach the preset target indoor CO_2 concentration, i.e. 2000 ppmV. Example calculations of two modelling scenarios (one with 1 person 'at rest' and another with addition of a person 2 with different anthropocentric parameters and activity level) with a set of *real-world* data (referred to as 'test input value' later) are presented in Table 2. Under Scenario 1, the model calculation implied that in a closed room of 12 × 12 × 10 m^3, respiration by one person at rest (1 MET with basal RQ of 0.83) of 65 kg body weight and

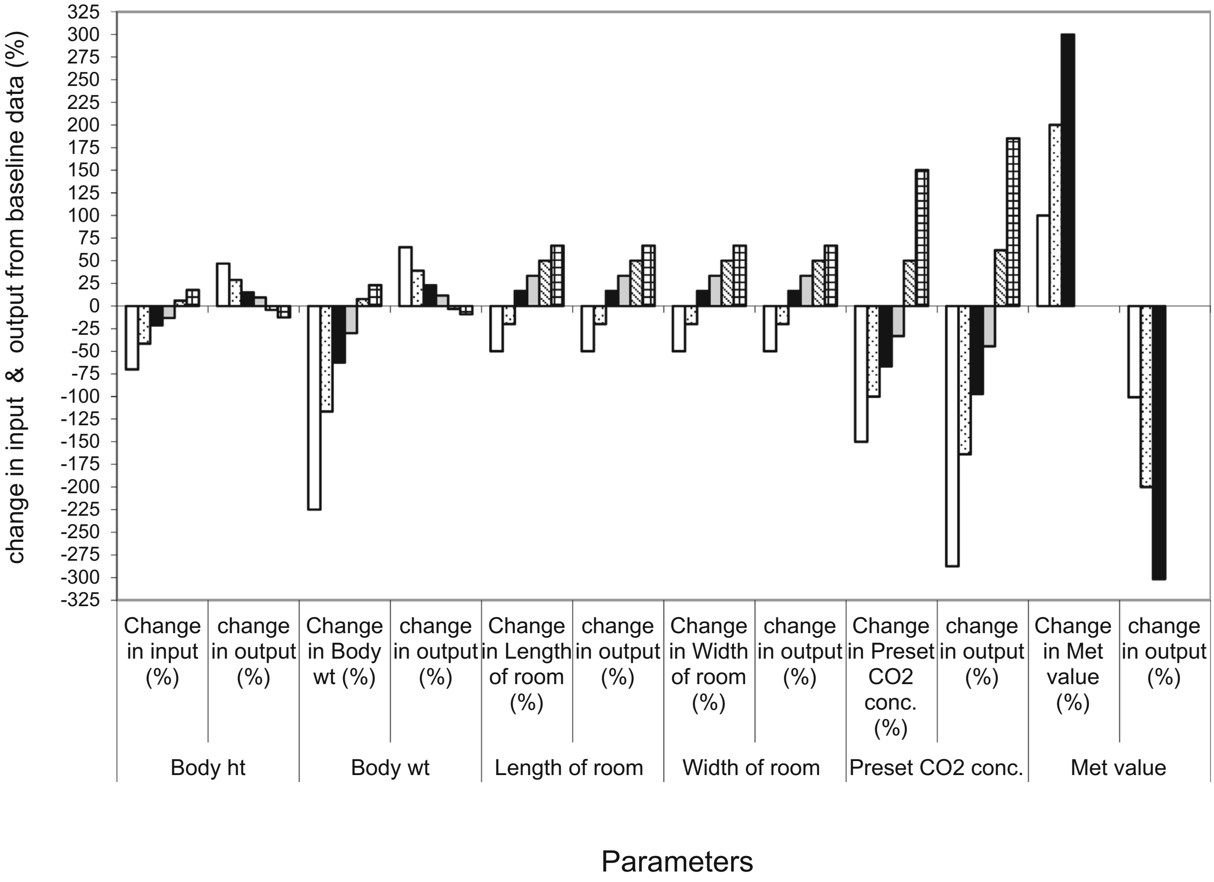

Fig. 3 Changes in degree of sensitivity with different values of input variables

1.7 m height would take about 4 h 23 min (or 4.38 h) to reach 2000 ppmV indoor CO_2 in the room when background indoor CO_2 concentration was 380 ppmV. Under scenario 2, when another walking person (at 0.9 m/s speed) is added (78 kg body weight and 1.9 m height, activity level of 2 MET with a basal RQ of 0.83) with the person at rest, target CO_2 is reached much rapidly, i.e. after 1.31 h. Therefore, additional persons with different anthropocentric parameters and activity levels would ensure that the same room attains 2000 ppmV CO_2 more rapidly. Therefore, the attainment of target CO_2 levels in a particular room would be dynamically governed by varying anthropocentric characters of occupants and their actual activity levels, and therefore, there cannot be a blanket desired occupant number for all types of rooms. So, by using the calculation guide presented in Table 2, the users need to create possible occupancy scenarios in their office or residence or schools or hospitals or prison *vis a vis* room dimensions, target activity levels and target CO_2 levels to fine-tune the most desirable room-wise number of occupants that would never allow to attain unsafe CO_2 levels within stipulated occupancy periods. The user can even preset a low target CO_2 level (e.g. < 800 ppmV) to fix the number of occupants in a definite room, ensuring healthier working and living environment.

The model output showed various degrees of sensitivity when made to run with different values of an input variable, keeping others constant. Changes in values of body height within a range of 1–2 m (− 41 to 18% over a test input value of 1.7 m) led to changes (in per cent) in output to the tunes of − 11 to 47% while changing body weight within a range of 20–80 kg (− 69 to 23% over the test input value of 65 kg) led to a more subdued response, i.e. − 8 to 65% changes in the output. Changing of room length, width and height within a range of 8–20 ft (− 33 to 66.7%) over the test input value of 12 ft led to exactly similar changes in the outputs. Changing the target CO_2 values within a range of 800–5000 ppmV (corresponding to − 60 to 150% variation over the test input value of 2000 ppmV) led − 74 to 185% variation over the test data output (Fig. 3). Variation in the MET values within a range of 1–4, corresponding to changes of 0–300% over the benchmark test input value of 1, led to changes of − 50 to − 75% in output, indicating proportional and inverse sensitivity. In summary, sensitivity analysis indicated that the model output was sensitive to all input values but the

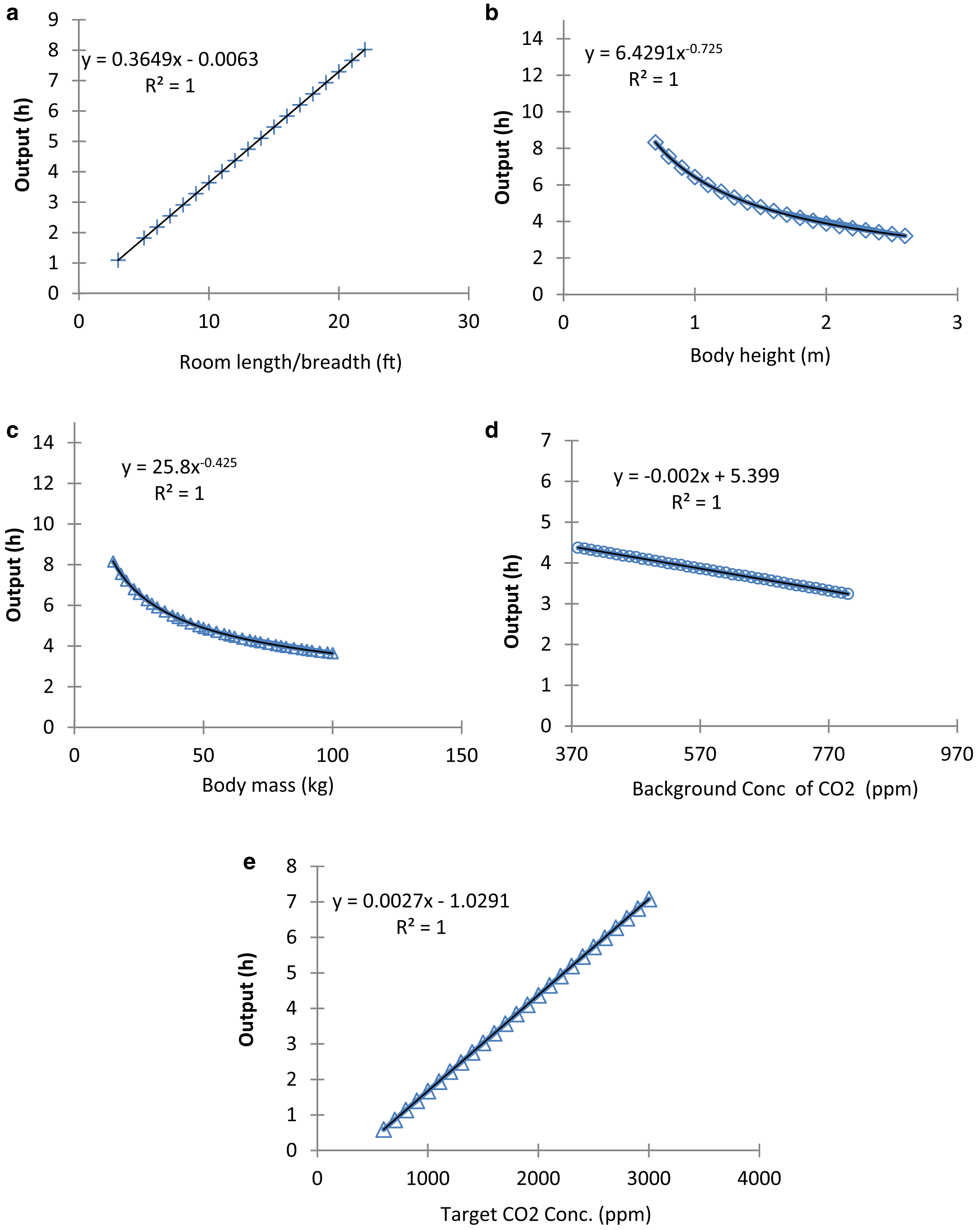

Fig. 4 Goodness and fit between input variables and output

greatest to target CO_2 value and body weight. Regression analysis for examining the goodness and fit of input variables with output revealed that output was either perfectly linearly related (room length and breadth vs. output; target CO_2 concentration vs. output; Background CO_2 level vs. output, inversely linear) or perfectly related by power function (body height and mass vs. output) with the input parameters, returning unit regression coefficients in each case (Fig. 4a–e).

During model validation experiments, it was noticed that there was low (Predicted:Observed − 0.7 to 0.88) to moderate (Predicted:Observed − 0.49 to 0.68) difference

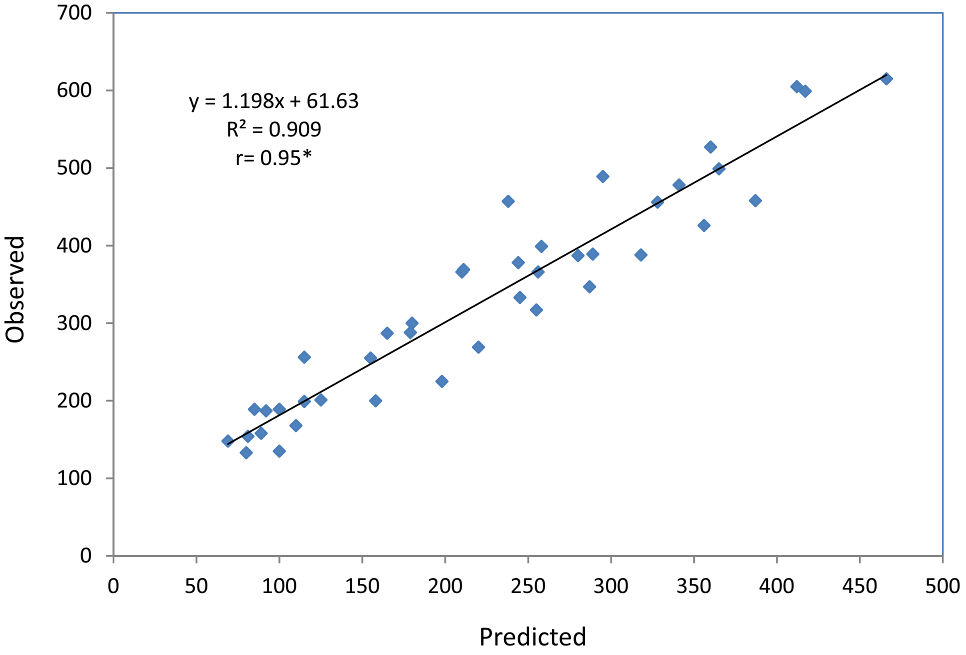

Fig. 5 Goodness of fit between predicted and observed time (minutes) in reaching various preset CO_2 target values

between the predicted and observed time in reaching various preset CO_2 target values. The model slightly underestimated the time required to reach preset target indoor CO_2 levels, but regression between observed (time) and predicted values (time) had a linear relationship with a high regression coefficient of 0.91 and a statistically significant Pearson correlation coefficient of 0.95 (at 95% confidence level) (Fig. 5). Therefore, actual time required to reach preset CO_2 level can be estimated from prdicted time with a reasonable degree of accuracy from the developed regression equation.

The critical importance of addressing uncertainty in scientific measurements have been discussed at length by various researchers [31–33]. Uncertainties in validation of this model might originate from: (1) Rooms were made airtight by tightly closing doors and windows and blocking visible gaps under doors and windows etc., but engineered leak-proofing techniques was not followed, (2) operation of ceiling/pedestal fans may not guarantee perfect homogeneous mixing of indoor CO_2, (3) CO_2 detectors have certain accuracy levels and hence have inherent uncertainty in measurements. Further, the inherent uncertainties in the model calculations, as discussed earlier, could also play a role in imparting uncertainties in calculations.

4. Conclusions

The model could be used as a decision-making tool to ascertain most desirable room occupancy that would not lead to build-up of uncomfortable or harmful levels of respiratory CO_2 in a ill-ventilated closed room. This could be especially useful for households, schools, commercial establishments, public halls, shops, hospitals, small court rooms or offices where indoor occupants stay or work for a long time without proper ventilation. This is commonly found in densely populated urban areas worldwide where increasing price and rents of personal and official spaces lead to cramming of small spaces. Also, outdoor air pollution and chilly winter conditions force occupants to stay and work in closed rooms, leading to suffocation and development of sick building syndrome from indoor CO_2 accumulation. Therefore, a numerical tool that could help take a decision on the maximum number of occupants that could be allowed to occupy an office space or house to maintain indoor CO_2 concentration within safe limits is welcome. The presented model would assist users to make a small programme in any preferable language or in spreadsheets for ready usage. The programme may be further fine-tuned at users' end with added or curtailed parameters to make it more robust and reliable after proper validation.

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