Achieving Sustainable Buildings: Balancing Energy Efficiency and Comfort through Ventilation Management

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Abstract

Proper ventilation management is essential for balancing energy requirements and limiting indoor CO_2 concentration. A high continuous ventilation rate ensures safe indoor CO_2 levels but significantly increases energy consumption. The high energy demand often leads building owners and occupants to prioritize meeting thermal requirements while neglecting the importance of indoor air quality. To optimize energy demand while maintaining thermal comfort and safe CO_2 limits, intermittent ventilation or reduced ventilation rates must be employed. Based on this study, different occupant densities provide varying ventilation time gaps to maintain CO_2 concentration within safe limits and offer an opportunity to save energy. For occupant densities higher than 50 m^3/person, a maximum ventilation gap of 250 minutes can be utilized, and the ventilation gap depends on the outdoor CO_2 level. For safe CO_2 levels at occupant densities above 20 m^3/person, continuous ventilation of 1.0 ACH suffices, while higher densities necessitate intermittent ventilation to cut energy demand. Energy use increases with higher ventilation rates and occupant densities, ranging from 1.25 to 2.28 times compared to the base case for 10 m^3/person to 90 m^3/person, respectively. Continuous ventilation at 2.0 and 3.0 ACH is required for lower occupant densities of 20 m^3/person and 10 m^3/person, which escalates energy use. So, it is recommended that lower occupant densities be avoided in indoor spaces. Tailored ventilation strategies can achieve approximately 50% energy savings in building operations.

Keywords: CO_2 concentration, intermittent ventilation, energy saving, occupant density, ventilation gap

1. Introduction

Human society is facing a lot of serious trouble in terms of environmental air pollutants and way of life. Indoor air quality (IAQ) is essential to enhance the quality of life, given that people spend most of their time in indoor spaces. Environmental pollution stands as a consequential and irreversible outcome of heightened energy consumption and the consequent combustion of fossil fuels. The International Environmental Agency reported that the rise in electricity demand on a global level in 2021 is 5%, which is almost met by fossil fuels (IEA, 2021). Total energy-related emissions increased by around 900 Mt between 2019 and 2023 with the growing development of major clean energy technologies such as solar PV, nuclear, wind, electric cars, and heat pumps. Otherwise, the expected increase in CO_2 emissions would have been threefold of emissions during the same period (IEA, 2023). In the year 2022, the global demand for air conditioning devices reached approximately 117.8 million units, marking the highest figure of the past decade and surpassing the peak recorded in 2019, which stood at around 116 million units (Statista, 2022). The global air quality based on the CO_2 concentration range underlined is in a good category 86% of the time. However, the Asia–Pacific (APAC) region belongs to the risk category approximately 10% of the time. The average CO_2 distribution highlighted in the Figure 1 for different regions. This data analysis is a collective representation of both the number of occupants present and ventilation. However, relying on simple statistics may not provide a comprehensive picture of the indoor air quality because occupancy densities play a vital role in CO_2 accumulation ("IAQ Data Benchmarks for 2023: What are Average Levels of PM2.5, CO_2, and TVOC in Different Regions?," n.d.). As shown in Figure 2 ("Press Release Ifrma Page: Press Information Bureau," n.d.), the AQI index can significantly impact ventilation requirements and underscores the limitation of relying solely on statistics for a comprehensive guideline. Figure 2 (a) illustrates the AQI distribution over the years based on the number of days, while Figure 2 (b) shows the monthly AQI distribution for various years.

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Figure 1: Global CO_2 concentration across all regions (a) percentage bar (b) daily indoor air distribution

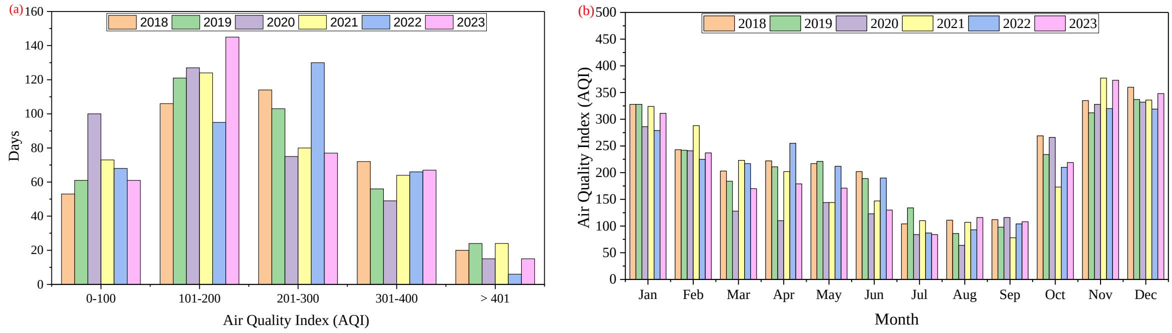

Figure 2: Delhi air quality index for different years (a) index division into days (b) monthly AQI level

A study was presented by (Baghoolizadeh et al., 2023) with the objective of achieving thermal comfort and improving CO_2 concentration through the optimization of genetic algorithms in residential buildings. Optimization results revealed that thermal comfort improved from 52% to 80%, and concentration of CO_2 improved, ranging from 17% to 30%. (Sakamoto et al., 2022) has been calculated CO_2 emissions rate per person and measured CO_2 concentrations in the control environment once it has reached to steady state. The emission rates per person varied from 14.1 to 17.8 L/h for sedentary work: higher emissions calculated in the afternoon might be because metabolism increases after diet. (Franco and Leccese, 2020) were estimated indoor occupancy through CO_2 concentration measurement for different types of activities. (Hussin et al., 2017) CO_2 measurements were observed in the university laboratory for 10 air-conditioned buildings and highlighted inadequate ventilation because CO_2 concentrations exceeded the limit of 1000 ppm. (Lawrence and Braun, 2006) have presented models for predicting indoor CO_2 concentrations, taking into account people as internal sources of emission. (Shriram and Ramamurthy, 2019) have emphasized that as recommended by ASHRAE, continuous ventilation results in high energy demand. (Salthammer, 2024) stressed the use of carbon dioxide as an air quality index because of fatal poisoning associated with it, and in indoor surveys, this substance receives less attention. (Krawczyk et al., 2016) conducted a CO_2 measurement in school buildings situated in Bialystok and Belmez and found that with medium occupancy, CO_2 concentration exceeded recommended values. (Borowski et al., 2022) experimentally observed in the occupant thermal comfort and indoor air quality of the hotel building. The analysis in a hotel building revealed that most of the time, occupants feel thermally comfortable; however, CO_2 concentration temporarily exceeded 2000 ppm. (Mahyuddin and Essah, 2024) considered CO_2 concentrations as a parameter to explore the ventilation strategies and design guidelines for classrooms. The research documented standard classrooms may have occupant densities in the range of 1.8- 2.4 m^2/ person. (Wargocki et al., 2002) unraveled indoor air quality improvement by enhancing air change rates; however, energy consumption for cooling and heating increased depending on the location and season. (Bakó-Biró et al., 2007) aimed to establish a link between occupant cognitive performance and air quality using a classroom atmosphere. By performing in-situ experimental measurements and considering CO_2 as an air quality indicator, the investigation revealed that low ventilation rates significantly decrease vigilance, attention, memory, and concentration. (Lu et al., 2010) developed a model for individual space for calculating CO_2 generation and ventilation rates in mechanically ventilated buildings. (Kim and Choi, 2019) inquired about the impact of increased outdoor CO_2 on the ventilation rate for buildings located in Shanghai, China. The research unveiled that to maintain indoor CO_2 levels with an increase in outdoor CO_2 levels, the outdoor flow rate needs to be increased.

The current amount of literature has extensively explored the challenges posed by the accumulation of CO_2 in indoor environments. Further research has also unveiled the potential for energy saving as a result of optimizing indoor air quality and thermal comfort. The comprehensive determination of ventilation cycle time or minimum ventilation requirement is imperative for the efficient operation of mechanical ventilation in spaces equipped with ductless air conditioning systems. Previous recommendations have resulted in high energy demand, emphasizing the need for accurate calculations to optimize energy consumption. By utilizing the ventilation cycle time, occupants can effectively reduce accumulated CO_2 concentrations in indoor spaces without the necessity of installing expensive sensors. The aim of this research is to evaluate the ventilation cycle time and potential of energy saving compared to recommended ventilation for different occupant densities and ambient CO_2 concentrations.

The analysis, detailed through numerical results and experimental model validation, includes the following objectives:

- Measuring indoor CO_2 concentration in the actual environment to validate the numerical model in office space.
- Analysing indoor CO_2 concentration levels based on outside concentration levels and indoor occupant densities.
- Determining the impact of ventilation rate on energy consumption and indoor CO_2 level for numerous occupant's densities.

2. Methodology

In several research studies, CO_2 as indoor air quality presented a concern for occupants; however, some denied the potential concern and stressed the other indoor quality parameters. The effect of other air quality parameters might have a strong potential to deteriorate the occupant's health compared to CO_2 concentrations. However, this research is focused on maintaining the CO_2 concentrations within the safe limit because other indoor air quality parameters have less concentration change in most indoor spaces than CO_2 levels. The variation in outdoor CO_2 concentration provides an understanding of the season and the effect of locations. To analyze the indoor CO_2 concentrations, a constant occupancy schedule was considered between 8:00 to 18:00 hours, and except this time, there is no occupancy associated with the building spaces. As a case study, we developed a two-story building (627.25 m^2) model through Design Builder located at the Indian Institute of Technology in Delhi (IITD), India. The main methodologies for this study were categorized in part:

- Measurement of indoor CO_2 concentration in an actual indoor environment to validate the numerical model.
- Calculation of the CO_2 concentration by numerical modeling for specific occupancy duration with constant building infiltration.
- Comparison of the impact of continuous ventilation rate on building energy demand and indoor CO_2 concentration.

Numerical modeling examines how insufficient air circulation can lead to elevated CO_2 levels, potentially compromising occupants' well-being. By exploring various occupant densities and outdoor CO_2 levels, the study investigates the impact of the continuous replacement of indoor air on energy consumption and indoor CO_2 regulation. The study also proposes intermittent ventilation operation as a strategy to effectively mitigate CO_2 concentrations tailored to different space dimensions and occupancy levels. The research aims to recommend optimal ventilation rates and operational time for different occupant densities to maintain thermal comfort and acceptable CO_2 levels while reducing energy usage. Additionally, it analyzes the patterns of CO_2 accumulation and dissipation over time across different outdoor CO_2 levels. The investigation scrutinizes a ventilation system's ventilation rate or operational intervals across different outdoor CO_2 levels and indoor occupant densities, as delineated in Table 1. The study evaluated through a building model based on the assumption of an infiltration rate of 0.2 ACH, attributing to leakage through cracks, and the occupant CO_2 generation rate of 4.16×10^{-8} m^3/s-W. The ACH is basically a unit of measurement of air circulation or replacement in a space, which stands for air changes per hour. The circulation or replacement of air in space can happen in controlled and uncontrolled ways. The transient air mass balance equation (eq. 1) calculates carbon dioxide concentration in zone air (<i>EnergyPlusTM Version 22.1.0 Documentation Engineering Reference</i>, 2022). The two-story building model at IIT Delhi is being considered for the analysis of energy-saving potential and validation purposes, as depicted in Figure 3. The details of the building dimensions, orientation, and envelope material properties are streamlined (Verma et al., 2023). The building space and envelope thermal properties important for building energy modeling have been delineated in Table 2 and Table 3, respectively.

Table 1: The numerical study parameters and variations

Parameter	Range
Outside CO_2 concentration (ppm)	150, 250, 350, 450
Occupant density (m^3/person) or (m^3/p)	10, 20, 30, 40, 50, 60, 70, 80, 90
Exhaust ventilation rate (ACH)	1.0, 2.0, 3.0
Infiltration (ACH)	0.2

Table 2: Overall building envelope and space information

Item	Description
Total conditioned area (m^2)	627.25
Overall window-to-wall ratio (WWR)	0.2
Number of floors	2
Floor to floor height(m)	3.5
Floor to ceiling height (m)	3.0
Window-sill height (m)	0.8

Table 3: Building envelope thermal properties

Building Element	Component layer	Component material	Material Thickness (m)	U-value (W/m^2K)
Exterior wall	Layer 1(outside)	Plaster	0.0125	
	Layer 2	Brick	0.225	1.566
	Layer 3(inside)	Plaster	0.0125	
Roof	Layer 1(outside)	Lime sand render	0.1	
	Layer 2	Reinforced Concrete	0.1	
	Layer 3	Cast Concrete	0.2	1.36
	Layer 4	Air gap	0.5	
	Layer 5(inside)	Gypsum (false ceiling)	0.01	
Ground Floor	Layer 1(outside)	Medium weight concrete	0.075	
	Layer 2	Brick	0.075	
	Layer 3	Concrete, Reinforced (with 2% steel)	0.0250	2.181
	Layer 4	Cement screed	0.025	
	Layer 5(inside)	Ceramic/clay tiles	0.025	
Internal partition	Layer 1(outside)	Cellulosic insulation	0.001	
	Layer 2	Plywood (Heavyweight)	0.025	2.180
	Layer 3(inside)	Cellulosic insulation	0.001	

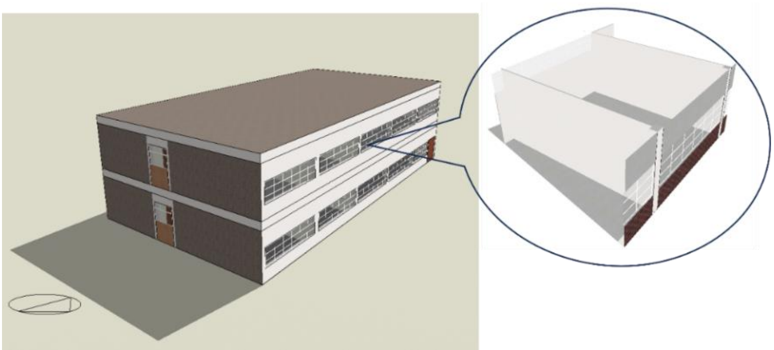

Figure 3: Building model used to calculate energy consumption and CO_2 concentration.

$$\rho_{air} V_z C_{CO2} \frac{dC_z^t}{dt} = \sum_{i=1}^{N_{sl}} kg_{mass_{sched\ load}} \times 10^6 + \sum_{i=1}^{N_{zone}} \dot{m}_i (C_{zi} - C_z^t) + \dot{m}_{inf} (C_\infty - C_z^t) + \dot{m}_{sys} (C_{sup} - C_z^t) \quad \text{(eq.1)}$$

Where $\sum_{i=1}^{N_{sl}} kg_{mass_{sched\ load}}$ indicates internal CO_2 load due to occupancy (kg/s), $\sum_{i=1}^{N_{zone}} \dot{m}_i (C_{zi} - C_z^t)$ denotes CO_2 transfer due to interzone air mixing (ppm-kg/s), $\dot{m}_{inf} (C_\infty - C_z^t)$ represents CO_2 transfer due to ventilation and infiltration of ambient air (ppm-kg/s), $\dot{m}_{sys} (C_{sup} - C_z^t)$ indicates CO_2 transfer due to system supply (ppm-kg/s). Furthermore, the terms $C_\infty, C_z^t, C_{zi}, C_{sup}$ represents the CO_2 concentration of outdoor zone air, the CO_2 concentration at the current time, the CO_2 concentration being transferred into this zone, and the CO_2 concentration in the supply air stream by the system, respectively, measured in parts per million (ppm). In addition, C_{CO2} indicates CO_2 capacity multiplier and V_z denotes zone volume (m^3).

This study simulated indoor CO_2 levels for various outdoor CO_2 concentrations and different air change rates per hour over a period of 10 hours, from 8:00 AM to 6:00 PM on a typical weekday. Generally, the indoor CO_2 concentration increased starting at 8:00 AM and continued to rise until 6:00 PM due to constant occupancy during this period. After these spaces were vacated, the CO_2 concentration began to decrease, continuing until the start of occupancy the following day. Atmospheric CO_2 levels vary with the time of day and exhibit seasonal fluctuations in any given location. Therefore, we considered different atmospheric CO_2 levels in the present study, which cover variations across seasons and locations. In all cases, the indoor CO_2 concentration was calculated for an infiltration rate of 0.2 ACH.

The numerical building model for CO_2 concentration was validated through experimental monitoring of indoor CO_2 levels. These concentrations were measured using a carbon dioxide probe connected to a microclimatic datalogger (HD32.1), as shown in Figure 3. The CO_2 sensor operates on the non-dispersive infrared (NDIR) principle with a dual-source configuration. The measurement uncertainty of the sensors is specified as ± (50 ppm + 3% of the reading) under standard conditions of 20°C, 50% relative humidity, and 1013 hPa. The validation results of the building model presented in Figure 5. The model was validated for building space known as the Thermal Devices Testing Laboratory (TDTL) at the Department of Energy Science and Engineering, IIT Delhi. The two-story building where the laboratory is located has a total area of 627.25 m², with the TDTL occupying approximately 30.79 m². A numerical analysis was performed to validate indoor CO_2 concentration by monitoring occupancy variations and the operation of the ventilation system from 10:00 to 16:30. The ventilation system was activated one hour prior to the experiment, at 09:00, to equalize the indoor CO_2 concentration with that of the ambient environment. During this period, the indoor space was maintained without occupancy and without the air-conditioning system in operation. The variations in occupancy and the switching on/off of the exhaust ventilation system are illustrated in Figure 5. Furthermore, the numerical and experimental results were presented, showing a strong agreement. The variation in numerical results fell within the uncertainty range of the carbon dioxide sensor measurements.

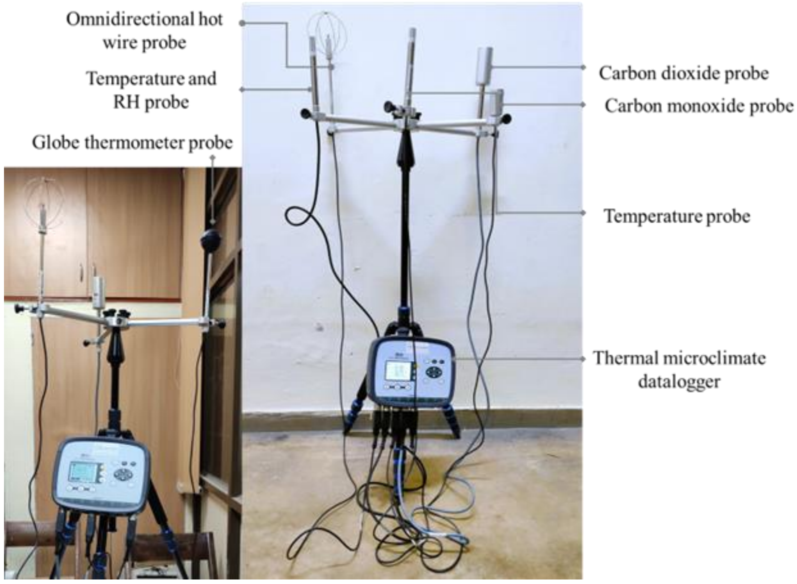

Figure 4: Thermal microclimatic datalogger HD32.1

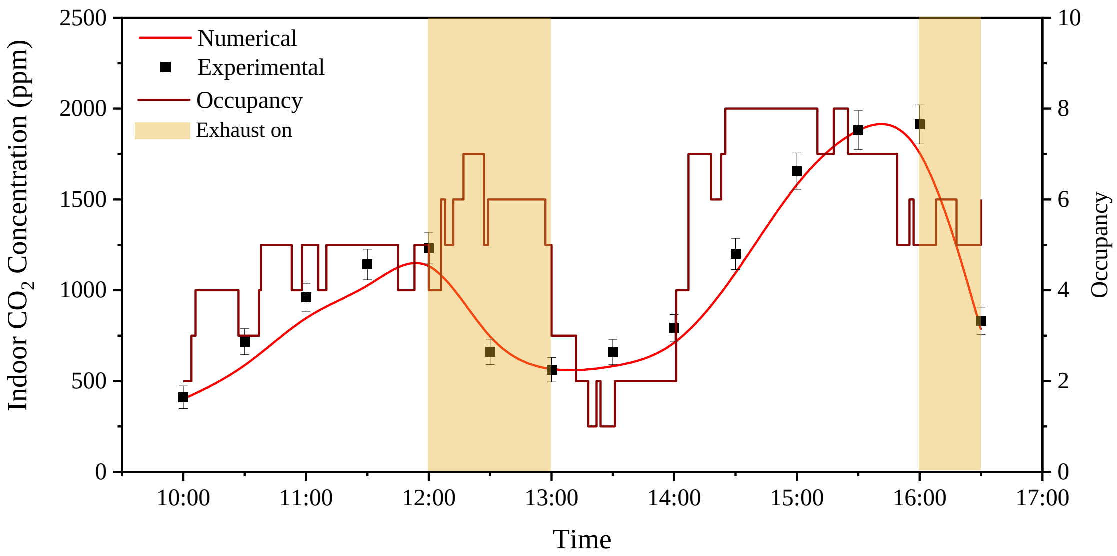

Figure 5: Model validation for CO_2 concentration

3. Results and Discussion

The calculation of CO_2 concentration for various occupant densities, ranging from 10 to 90 m^3/person, and different outdoor concentrations was performed using computational modeling with Design Builder and Energy Plus. The study considered a 10-hour occupancy period from 08:00 to 18:00, during which the CO_2 concentration was monitored starting at 08:00, as accumulation began with the onset of occupancy. After the unoccupied period starting at 18:00, the CO_2 levels began to decrease due to building infiltration alone, as illustrated in Figure 6. The study has been conducted for occupant densities varying from 10 m^3/person to 90 m^3/person during the occupied period from 08:00 to 18:00. The safe CO_2 concentration limit considered 1,000 ppm, as highlighted in Figure 6 since exposure to concentrations above this threshold has been linked to neurophysiological symptoms such as headaches, fatigue, and difficulty concentrating (Muscatiello et al., 2015). In addition, Figure 5 illustrates the variation in indoor CO_2 concentration over time as a function of occupant density under different outdoor CO_2 concentrations. The four outdoor CO_2 concentrations analyzed in the study were 150 ppm, 250 ppm, 350 ppm, and 450 ppm. Unintentional infiltration occurred through cracks in the building envelope as well as through doors and windows. This infiltration significantly impacts both energy consumption and indoor CO_2 concentration levels. To address this, the study assumed a constant infiltration rate of 0.2 ACH for both occupied and unoccupied periods. Maintaining a lower infiltration rate helps to minimize energy consumption while ensuring thermal comfort for occupants during occupied periods.

Figure 6 (a) illustrates the accumulation of indoor CO_2 concentrations at varying occupant densities, assuming an outdoor CO_2 concentration of 150 ppm. For occupant densities exceeding 80 m^3/person, CO_2 levels remain below 1000 ppm during the 10-hour occupied period. However, lower occupant densities result in CO_2 concentrations surpassing safe limits. Occupant densities below 50 m^3/person are particularly critical, as indoor CO_2 concentrations increase rapidly, exceeding 2000 ppm. A decrease in occupant density results in faster CO_2 accumulation. In scenarios without ventilation, indoor CO_2 concentration exceeds the safe limit within the occupied period for all mentioned occupant densities. Specifically, for occupant densities of 40 m^3/person and below, the safe CO_2 limit is surpassed within 200 minutes of occupancy duration. For occupant densities above 50 m^3/person, mandatory ventilation is not required until 250 minutes of occupancy duration. In spaces with an occupant density of 10 m^3/person, CO_2 concentration rapidly exceeds the safe level, necessitating mandatory ventilation within 60 minutes of occupancy. Similarly, for an occupant density of 20 m^3/person, ventilation is required within 90 minutes of occupancy to maintain a safe CO_2 level. Furthermore, for occupant densities of 10 m^3/person, ventilation is needed at the beginning of the next occupancy period to release accumulated CO_2, as an infiltration rate of 0.2 ACH is insufficient to reach outdoor CO_2 levels. Therefore, it is advisable to provide ventilation before the start of the next occupancy period for occupant densities below 20 m^3/person, which will also help in saving energy. Furthermore, the accumulation of indoor CO_2 concentration for numerous occupant densities for different ambient CO_2 levels has been illustrated in Figure 6 (b, c, d). As outdoor CO_2 concentration increases, the occupant densities cross the safer limit of CO_2 concentration in less time. This signifies that outdoor CO_2 concentration levels are crucial in ventilation requirements and energy consumption. Moreover, the detailed ventilation gap analysis for all outdoor CO_2 concentrations and occupant densities has been outlined in Table 4.

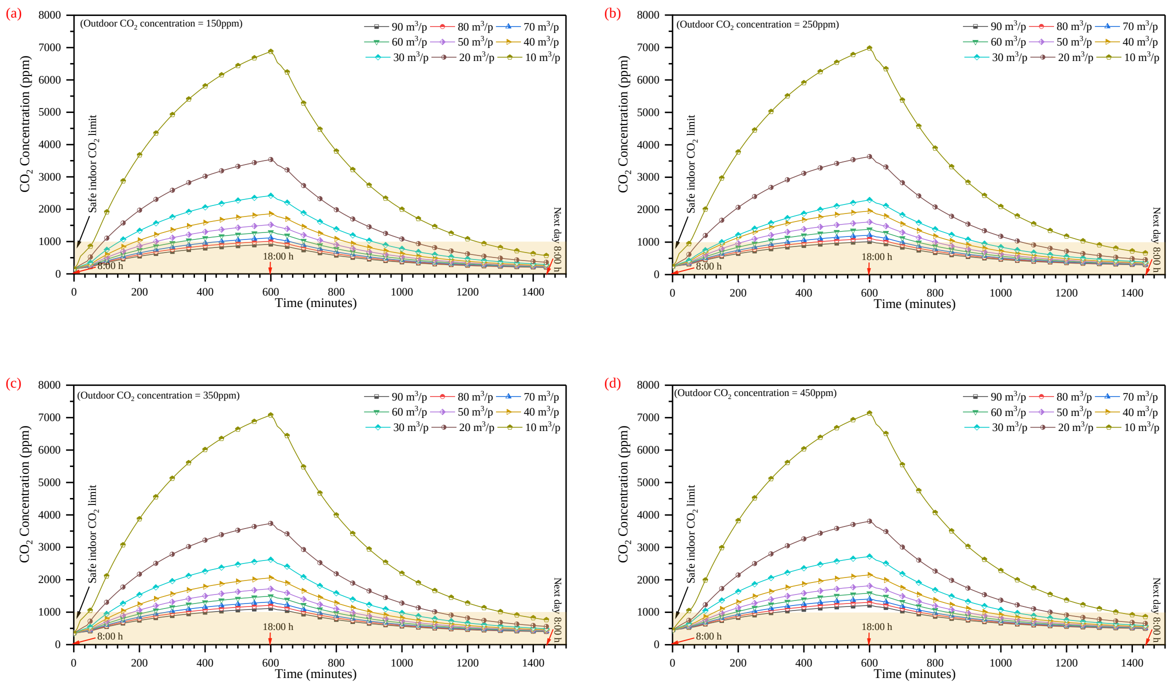

Figure 6: The impact of occupant density on indoor CO_2 concentration in case of no ventilation for outdoor concentrations (a) 150 ppm, (b) 250 ppm, (c) 350 ppm, (d) 450 ppm.

Table 4: Ventilation gap analysis for indoor space for different ambient CO_2 level

Ambient CO_2 concentration	Occupant densities (m^3/person)								
	90	80	70	60	50	40	30	20	10

(ppm)	Approximate time (minutes) to cross indoor CO_2 concentration above the safer limit								
150		580	450	330	250	190	150	90	60
250	570	440	350	270	210	170	140	85	55
350	410	335	285	220	180	140	110	80	45
450	320	270	245	190	160	125	95	80	45

Ventilating indoor air to the outdoors helps reduce indoor CO_2 concentration by introducing lower-pollutant outdoor air into building spaces. However, this process also increases the building's energy consumption due to the influx of hot or cold ambient air into indoor spaces. The energy consumption is influenced by both the ventilation rate and the surrounding environmental conditions. This study conducted calculations with ventilation rates ranging from 1.0 ACH to 3.0 ACH in intervals of 1.0 ACH. Atmospheric conditions significantly affect building energy consumption, and for the purpose of comparison, the environmental conditions were kept constant across all cases. Energy consumption varies substantially throughout the year due to fluctuations in the building's thermal load, with the highest thermal loads occurring during the summer. This study provides a comparative analysis of the annual energy consumption related to both cooling and heating requirements. Figure 7 presents a comparison of energy consumption in relation to variations in occupant density and ventilation rates. As illustrated in Figure 7, higher occupant densities result in lower energy consumption compared to lower occupant densities. Notably, energy demand increases significantly when occupant density falls below 30 m^3/person for the same ventilation rate. The lower occupant densities necessitate higher energy consumption because the present location belongs to a cooling-dominated region. The reduced occupant density leads to greater indoor heat accumulation due to the metabolic rate of individuals. Additionally, increasing ventilation rates in response to elevated atmospheric CO_2 concentrations further exacerbates energy consumption. The energy consumption changes with the ventilation rate, and the comparison of the energy requirement is calculated as depicted in Figure 8 for different ventilation rates with the base case (no ventilation). The energy consumption for the building in the case of a 1.0 ACH ventilation rate varies from 1.25 to 1.54 times higher than the base case scenario (no ventilation) for occupant densities 10 m^3/person to 90 m^3/person. The increase in energy consumption is higher for higher occupant densities than in comparison with no-ventilation. For the ventilation rate 3.0 ACH, the energy consumption increased from 1.66 and 2.28 times for occupant densities 10 m^3/person and 90 m^3/person as compared to no ventilation case. However, the increase in energy consumption may discourage building owners from providing continuous ventilation in indoor spaces.

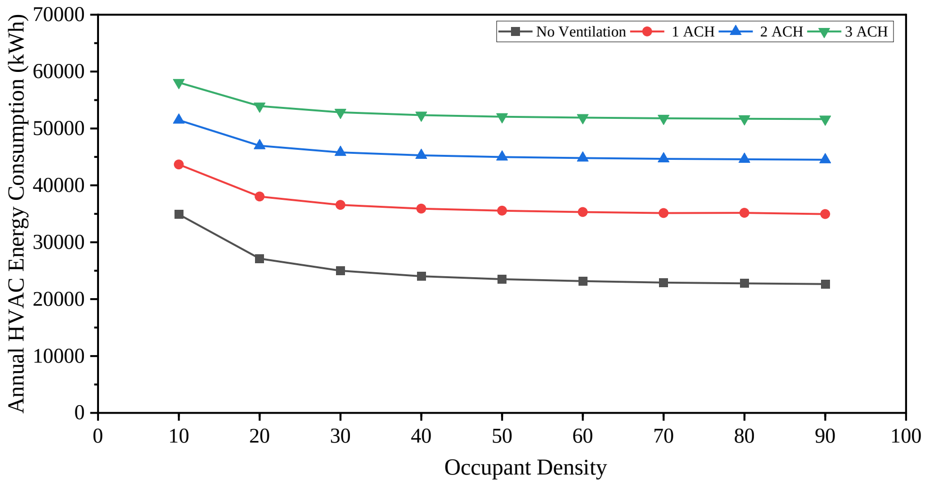

Figure 7: Annual energy consumption of building to maintain thermal comfort

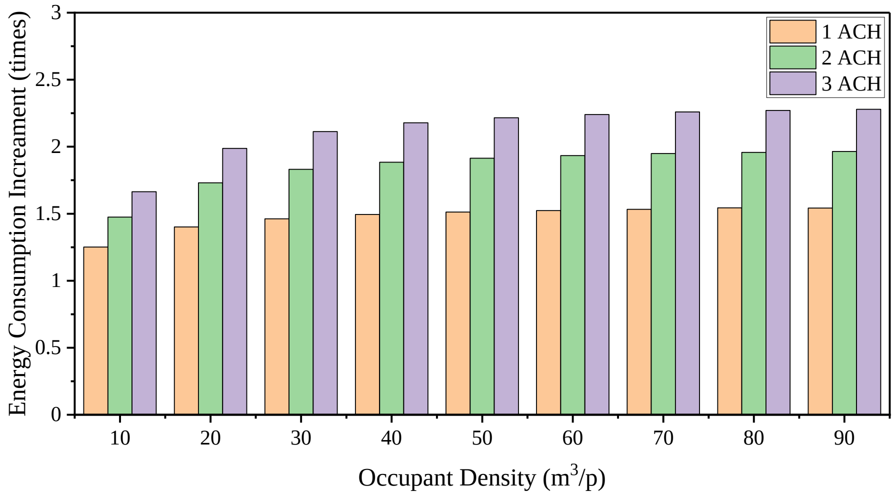

Figure 8: Comparison of energy consumption with no ventilation

Based on the different continuous ventilation rates, indoor CO_2 concentration presented in Figure 9 for outdoor CO_2 concentration of 450 ppm. Ventilation was provided during the occupied period only, and indoor CO2 concentration diffusion happened during the remaining time due to the building's infiltration of 0.2 ACH. The continuous ventilation rate of 1 ACH, as illustrated in Figure 9 (a) occupant densities of 10 m3/person and 20 m^3/person crosses safe indoor limits. Furthermore, 2.0 ACH continuous ventilation maintains indoor CO_2 concentrations for all occupant densities except 10 m^3/person. The spaces with occupant density 10 m^3/person required a continuous ventilation rate of 3 ACH. A continuous ventilation rate of 3 ACH is sufficient to maintain safe indoor CO_2 concentrations. For higher occupant densities above 50 m^3/person, intermittent ventilation can provide significant energy savings. Furthermore, the ventilation rate must be controlled according to the outdoor AQI level because severe AQI regions might worsen indoor air quality due to the exchange of indoor air with outdoor air. As illustrated in Figure 2 Delhi's air quality index reaches severe conditions that require avoidance of ventilation in these days.

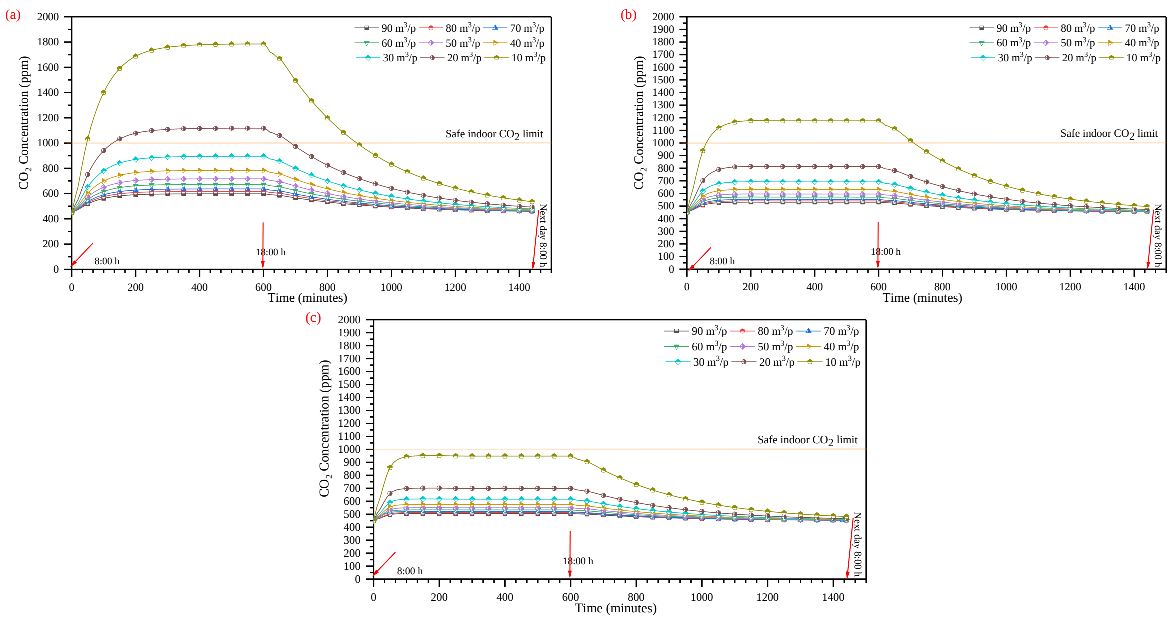

Figure 9: Indoor CO_2 concentration for 450 ppm outdoor CO_2 level with ventilation (a) 1.0 ACH (b) 2.0 ACH (c) 3.0 ACH

4. Conclusions

In this study, indoor CO_2 concentration was evaluated for numerous outdoor CO_2 levels and occupant densities. Based on the two-story building model, a detailed analysis has been done to compare the energy consumption to maintain thermal comfort and air quality for different scenarios. The present study reinforces that inadequate ventilation diminishes indoor air quality by accumulating CO_2 released by occupants. The annual energy consumption can be reduced by controlling the ventilation rate based on indoor occupant densities. The main objective of the research was to enhance indoor air quality and control energy consumption by assessing mandatory ventilation requirements for different occupancy scenarios. The findings revealed that adapting different ventilation rates for different occupant densities provides less energy losses. The conclusions of this work are outlined below:

- Energy consumption escalates with increased ventilation rates and occupant densities, ranging from 1.25 to 2.28 times the base case (no ventilation). Specifically, at 1.0 ACH, energy consumption rises between 1.25 and 1.54 times, while at 3.0 ACH, it increases from 1.66 to 2.28 times in comparison with the base case for occupant densities ranging from 10 m^3/person to 90 m^3/person respectively. Therefore, optimizing ventilation is crucial for balancing energy efficiency and indoor air quality.
- Occupant densities exceeding 20 m^3/person require a maximum continuous ventilation rate of 1.0 ACH to maintain a safe indoor CO_2 concentration limit of 1000 ppm. For higher occupant densities, intermittent ventilation, as outlined in Table 4, can be utilized to maintain safe CO_2 levels and ensure thermal comfort, thereby further reducing energy demand.
- This analysis indicated that maintaining a safe CO_2 concentration at an occupant density of 20 m^3/person requires a continuous ventilation rate of 2.0 ACH, while a density of 10 m^3/person necessitates 3.0 ACH. This escalation in ventilation rates results in an increased energy demand, ranging from 1.17 to 1.27 times higher for 2.0 ACH and 1.33 to 1.47 times higher for 3.0 ACH, compared to a baseline of 1.0 ACH. Consequently, it is recommended that building owners limit occupant density to above 20 m^3/person to optimize energy efficiency and maintain indoor air quality.
- After a nighttime occupancy gap, indoor CO_2 levels were near the ambient level for most of the occupant densities. At the start of occupancy in the morning, low CO_2 levels in indoor spaces can be leveraged to save energy by delaying the operation of the ventilation system. Without ventilation, indoor CO_2 levels exceed the safe limit after 45 minutes of occupancy at a density of 10 m^3/person. This time frame extends with higher occupant densities and can be strategically utilized based on building operation scenarios.
- Implementing tailored ventilation strategies based on specific building scenarios can save up to 50% of building energy. Post-night occupancy, leveraging ambient CO_2 levels can also save further energy.

This research will assist policymakers and building owners with specific requirements in developing a comprehensive roadmap for optimizing energy efficiency and maintaining safe indoor air quality under varying occupancy and outdoor conditions. Furthermore, this study was based on constant occupant densities over a 10-hour duration, considering an infiltration rate of 0.2 ACH. However, actual building spaces may experience fluctuations in occupant density over short timeframes. These variations may not significantly impact energy demand, but further research is needed to determine more precise ventilation time. Moreover, a detailed analysis might be helpful in more accurate ventilation interval analysis for different types that represent different infiltration.

5. Acknowledgments

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