Environmental Research and Technology
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DOI: https://doi.org/10.35208/ert.1084052

Research Article

Indoor air CO_2 concentrations and ventilation rates in two residences in İzmir, Turkey

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ARTICLE INFO

Article history
Received: 07 March 2022
Revised: 19 April 2022
Accepted: 30 April 2022

Key words:
Air exchange rate; Building monitoring, CO_2 concentration; Infiltration rate; Ventilation rate

ABSTRACT

Houses are the places where people spend most of their time. That is why indoor air quality at home is essential for public health. Sufficient ventilation is the factor to avoid accumulation of pollutants in indoor air, which include microorganisms, such as SARS-CoV-2. Therefore, adequate ventilation is needed to provide good indoor air quality for human health and reduce infection risk at home. There are no reports of residential ventilation rates in Turkey. In this study, CO_2 concentrations were measured in two residences in Izmir, Turkey. Three experiments were conducted to determine background concentrations and the rate of natural ventilation with infiltration and opening windows. Results show that air exchange provided by infiltration is low for both case rooms, while adequate ventilation could be achieved with natural ventilation under the studied conditions. Infiltration provided air exchange and ventilation rates of 0.18 h^{-1} and 5.9 m^3/h for Case 1 and 0.29 h^{-1} and 8.23 m^3/h for Case 2, respectively. Air exchange and ventilation rates were increased to 2.36 h^{-1} and 76.9 m^3/h for Case 1 and 1.2 h^{-1} and 34 m^3/h for Case 2, respectively, by opening the windows. Although ventilation can be provided by opening the windows, the other factors that determine its rate, e.g., meteorological variables, cannot be controlled by the occupants. Consequently, people cannot ensure the good indoor air quality in bedrooms and sufficient reduction in transmission of pathogenic microorganisms; therefore, risk of spreading diseases such as COVID-19 at home.

Cite this article as: Taşer A, Uçaryılmaz S, Çataroğlu I, Sofuoğlu SC. Indoor air CO_2 concentrations and ventilation rates in two residences in İzmir, Turkey. Environ Res Tec 2022;5:2:172–180.

INTRODUCTION

Ventilation is the key to good indoor air quality in any built environment. When a space lacks it, there starts an accumulation of – especially indoor-generated – pollutants [1]. The accumulation results in indoor air pollutant concentrations of 2 to 5, and sometimes 100 times, higher than those outdoors. Indoor sources of pollutants include people. In cases when there is a respiratory infection, people become a source of pathogenic microorganisms. When this occurs in

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Published by Yıldız Technical University Press, İstanbul, Türkiye

a space that lacks sufficient ventilation, there starts accumulation and transmission of the microorganisms, including SARS-CoV-2, the virus that causes COVID-19 disease [2–5]. Therefore, the ventilation rate or fresh air exchange rate becomes a significant factor for public health for indoor air quality and associated human health risks [2, 6].

Houses are the built environments where the most time is spent in a day. Family members sharing the same house regularly interact with each other while doing everyday activities such as watching TV, eating, or using the same bathroom. It is challenging to act by social distance rules at home; therefore, if any family member gets infected, this increases the probability of transmission to the other family members. Like all built environments, houses need to be resilient due to many anticipated pandemics and climate change.

Ventilation at home is essential to ensure good indoor air quality and a reduced risk of pathogenic microorganism transmission [7]. Although natural ventilation plays an active role in improving indoor air quality, the rate of fresh air exchange it provides is not controlled by people. It generally cannot provide adequate outdoor airflow in residences [8]. The average air exchange rate (AER) was reported to be 0.64±0.30 h^{-1} in apartments and 0.45±0.22 h^{-1} in houses in Europe [9], in which AER <0.5 h^{-1} occupants are more likely to experience non-specific symptoms.

Although there is no worldwide standardized definition of indoor air quality, various standards have been published in different countries. For example, EN 15251, one of the most widely used standards, is the first European standard to include criteria for four indoor environmental factors: thermal comfort, air quality, lighting, and acoustics. Turkey has no national ventilation standard, but the EU standard, EN 15251 is valid as TS [10]. ASHRAE 62.2 [11] specifies the minimum ventilation requirements for acceptable indoor air quality in residences in USA, applicable to both new and existing homes (Table 1).

The literature shows that indoor air quality and occupant health can be improved by retrofitting a mechanical ventilation system [12]; Kang et al. [13] studied 40 homes in Chicago and showed that putting an HVAC system into operation resulted in significant reductions in CO_2, NO_2, PM_1, $PM_{2.5}$, and PM_{10} concentrations with an average between 33 and 42%. In Portugal, indoor air quality of 10 residences was investigated for suitability of the ventilation during the sleep period [14]. AER was measured using CO_2 as the tracer gas, which the occupants emit. It was determined that all bedrooms had average AERs greater than the minimum value of 0.7 h^{-1} [15]. Pollutant concentrations indoors and outdoors of 40 typical residences in the temperate climate zone in Australia were measured [16]. Energy-efficient designs of newer, more airtight homes generally result in high indoor air pollutant concentrations as they trap the pollutants indoors. Therefore, a negative correlation was observed between residential age and selected indoor air pollutants. In addition, pollutant concentrations found during the study were lower than those found in other Australian and overseas studies.

Table 1. Ventilation rate recommended for residences by ASHRAE [11]

	People outdoor air rate (Rp)		Area outdoor air rate (Ra)	
Building type	Cfm/person	(L/s) x person	Cfm/ft^2	L/s x m^2
Residential	5	2.5	0.006	0.3

Although there are many studies abroad in the literature, three of which are exemplified above, there are no reports of ventilation rates in houses in Turkey. This study aimed to determine the ventilation rate by measuring CO_2 as the tracer gas in two residential dwellings in İzmir, Turkey. Real-time monitoring of CO_2 levels was conducted for three days indoors and outdoors with two ventilation scenarios.

MATERIALS AND METHODS

Residences

The Case 1 building is located in the Karşıyaka district of İzmir, at 38°27'54.2" North and 27°06'03.7" East. It is a ground + 4 apartment building with five apartments, occupying 140 m^2 areas on the ground floor. The building has a double facade, North and South. There are three bedrooms on the South facade. There is a kitchen and a living room on the North facade. A 9-meter-long balcony connects these. There is a distance of 10 m between the North facade (i.e., the main facade facing the road) and the neighboring building opposite it. Therefore, it can be said that it is highly hindered in terms of wind and daylight, especially since it is on the North side. There is a neighboring building on the east side of the building. There is a distance of two meters between the West facade and the neighboring building. Despite this, the absence of any windows on the West facade indicates that the land on which this building is located is an adjacent array according to the regulation. The examined apartment has a gross area of 120 m^2. It is a 3+1 apartment with three rooms facing South and a kitchen and living room facing North. The room in which the experiment was conducted in the family room facing the South. The gross floor area of the room is 14.42 m^2, and the net floor area is 11.41 m^2. In addition to floor areas, the total volume of the family room is calculated as 41.10 m^3, and the net volume is 32.52 m^3. There are two windows and one door in the case room.

The Case 2 building is a dwelling located in the Örnekköy neighborhood, Karşıyaka, İzmir. The coordinates are 38°29' 2" N 27°6' 9" E, and the elevation above the sea level is 94.1 meters. The building is located in a housing complex with two buildings. The case building is constructed with two

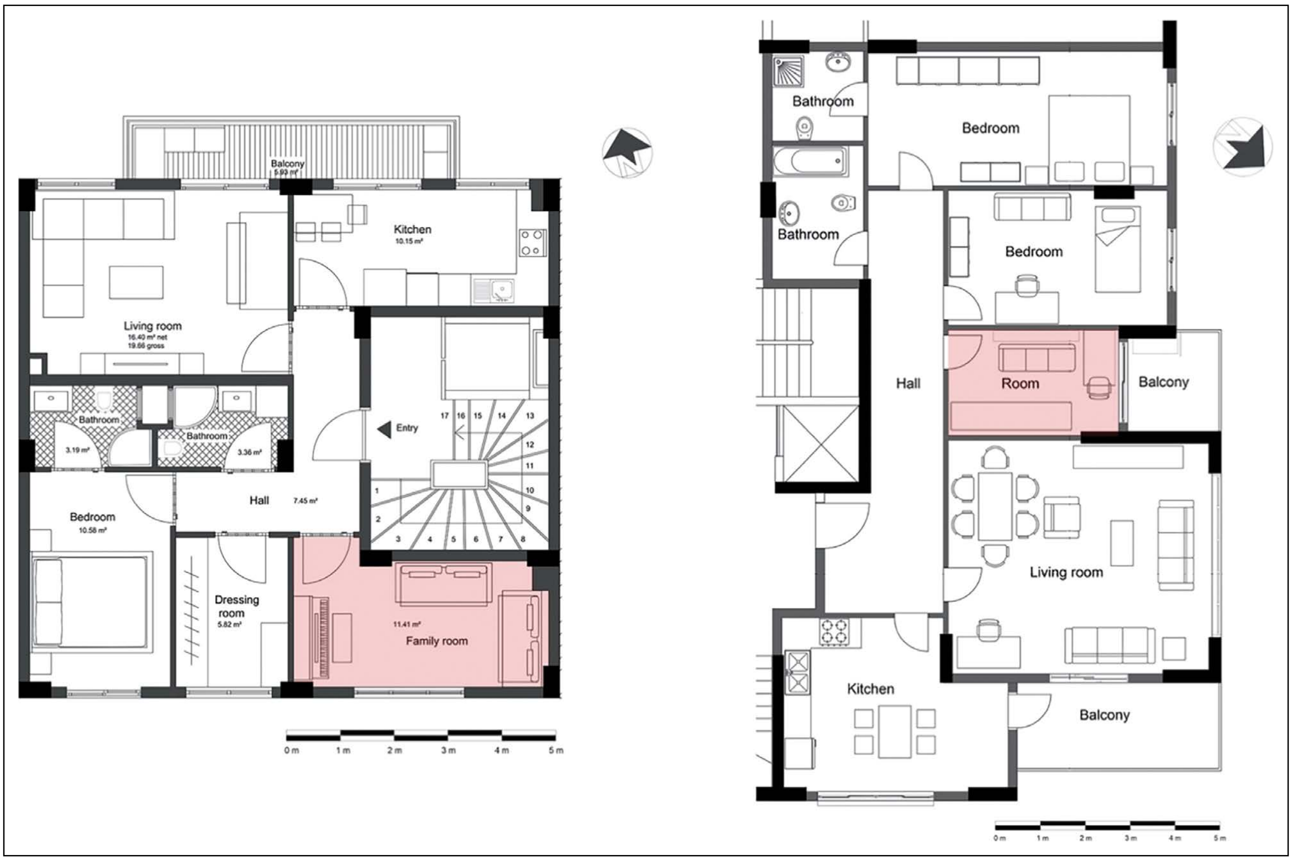

Figure 1. Left: Case 1 floor plans of case buildings and case rooms indicated with red color hatch. Right: Case 2 floor plans of case buildings and case rooms marked with red color hatch.

different entrances and two other cores, but the roof and walls are typical. There are nine flats, and each flat has two apartments. On the ground floor, there is one apartment, so the entire building has 10 stories. The surrounding of the building is quite empty. It is located next to a small hill. The case building is oriented to the North at 21° degrees. The gross dwelling area is 155 m^2, the net usable space is 122.20 m^2, and the total volume is 387 m^3. The dwelling contains three bedrooms, one kitchen, one living room, two bathrooms, and two balconies. The case room is a bedroom that is not being used. The case room's gross and net floor areas are 13.5 m^2 and 11.3 m^2. The gross volume is 36.45 m^3, and the net volume is calculated as 28.25 m^3. There is a balcony door and a room door in the case room. The floor plans of the two cases are presented in Figure 1.

Monitoring

A monitoring device (Testo 400) was used to measure the indoor and outdoor CO_2 levels of case rooms (Fig. 2). The device was located in the center of the room and placed on a chair. It was set to a 10-minute recording interval for three days. On the first day, outdoor CO_2 concentration levels were measured, and indoor CO_2 level was monitored for 12 hours representing the general (background) conditions. On the second day, 500 gr amount of dry ice was located in the room, and a monitoring process was conducted for 24 hours. Windows and the room door were kept closed to measure ventilation by infiltration. After 24 hours, CO_2 concentration levels were decreased to the general condition levels. Then, the door and windows were opened to reduce the concentration to the outdoor levels. On the last day, 250 gr of dry was located in the case room. After two hours of the monitoring process, the windows were opened to increase the natural ventilation. During monitoring with dry ice, a fan was used to obtain better mixing in the room. The range and accuracy values of the monitoring device are shown in Table 2.

Ventilation Rate Estimation

CO_2 is an important indoor air pollutant frequently used in such studies to investigate indoor air quality. CO_2 in the outdoor air varies between 330 and 500 ppm depending on the characteristics of the environment. The CO_2-based method is divided into three segments. The first is the occupancy phase or the concentration trend into build-up, the second is the steady-state, and the third is the decay (or "step-down") phase [17]. When an area is populated with people and then emptied (or when a controlled loading is

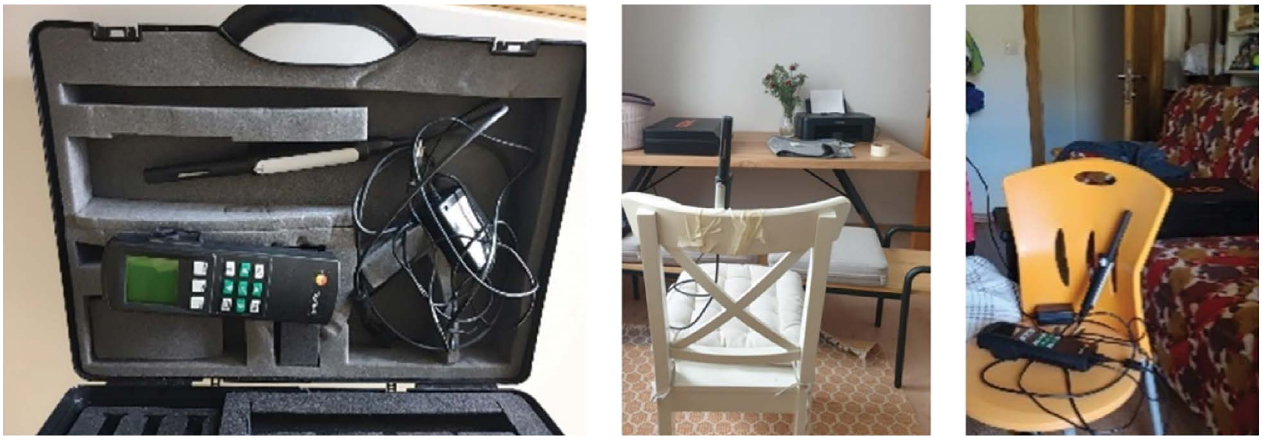

Figure 2. Testo data-logger placement.

Table 2. Indoor-outdoor monitoring equipment specifications

Sensor	Measuring range	Resolution	Accuracy
Testo 400 data-logger	0–10,000 ppm	1 ±	±(50 ppm+3% interval value) (0–5,000 ppm) (100 ppm+5% measurement value) (5,001–10,000 ppm)

done and left to monitor), or if there is a gradual decrease in occupancy, it makes sense to use decay or reduction to estimate the ventilation rate of the environment. The decay method is a technique that uses tracer gas dilution to determine the air exchange of a single zone with the outside environment induced by weather conditions. This test method is not limited to any single tracer gas [18]. The associated data analysis assumes that a single value can characterize the tracer gas concentration within the zone. Dry ice was used in this experiment to increase the CO_2 level in the indoor environment. In experiments, occupant density in the room could also be used for CO_2 production since people give CO_2 to the indoor environment due to breathing. A person engaged in a typical job produces 20 liters (0.02 m^3) of CO_2 per hour [19]. For this experiment, 21 people were required for 1 hour in a room with a volume of 30 m^3 for a CO_2 level of 10,000 ppm. Therefore, dry ice was preferred for ease of testing.

The monitoring results were imported to MS Excel for analysis. Equation-1 was used to calculate the air exchange rate in the room. In this equation, *AER* is the air exchange rate, and it is calculated by using duration and indoor and outdoor CO_2 concentration levels (Eq. 2). *t* is defined as the period during measurement. C_0 and C_t are measured CO_2 concentrations over the decay period (ppm). C_{ext} is CO_2 concentrations level (ppm) outdoors [19]. Although there is no exact value as the limit for CO_2 concentration, 1,000 ppm is the most commonly used value [11, 20] since Pettenkofer first proposed it in the 1800s. Therefore, the acceptable limit value of carbon dioxide in the room for this experiment was set as 1,000 ppm.

$$AER=Q/V \quad (1)$$

$$AER=t^{-1} \times \ln((C_o-C_{ext})/(C_t-C^{ext})) \quad (2)$$

where *AER* is Air Exchange Rate, *t* is the period between measurements (h), C_o and C_t are the measured CO_2 concentrations (ppm) over the decay period, and C_{ext} is outdoor CO_2 concentration (ppm) [17].

$$Q\ (m^3/h)=AER\times \text{room volume}\ (m^3) \quad (3)$$

where *Q* is ventilation rate.

RESULTS AND DISCUSSION

Experiments were conducted in two residential cases, i.e., Cases 1 and 2. Three experiments were conducted in each house. Firstly, indoor CO_2 levels were monitored for 12 hours without any dry ice or potential CO_2 source to assess the background concentration levels. In the second experiment, dry ice was placed in the room to increase CO_2 levels. Doors and windows were kept closed to measure ventilation by infiltration. In the last experiment, windows were opened after CO_2 levels exceeded a specified level, to measure an increased natural ventilation rate.

Background Concentrations

Indoor air CO_2 concentration levels were monitored for 12 hours. This experiment aimed to estimate general (background) CO_2 levels of the indoor environment without any potential CO_2 source. For the first case, the concentration levels varied between 437–562 ppm with an average value of 479 ppm (Fig. 3). For the second case, concentration lev-

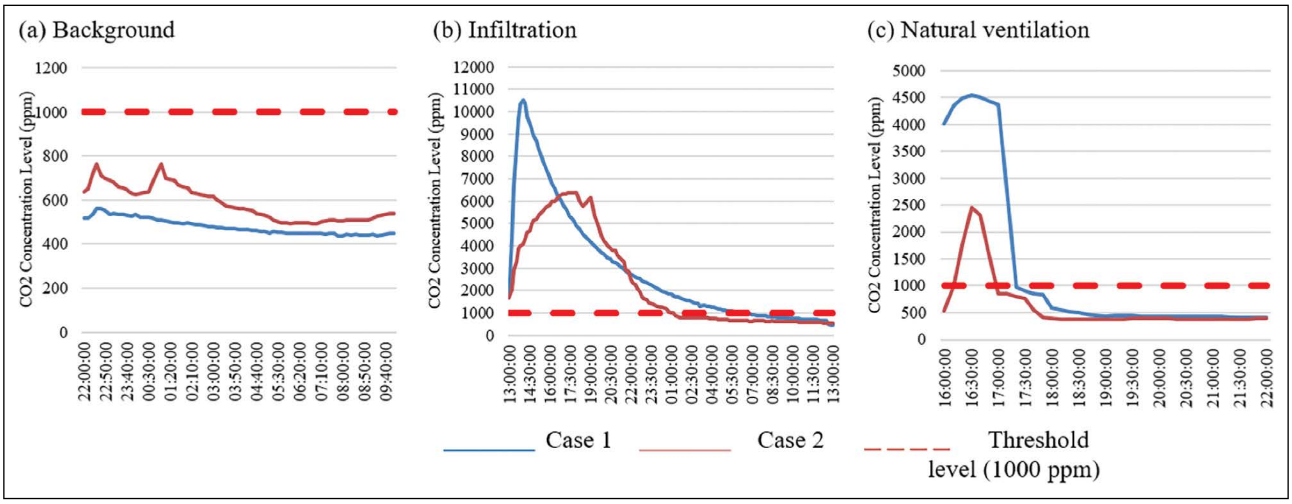

Figure 3. CO_2 concentrations measured during the experiments: **(a)** background, **(b)** infiltration, **(c)** natural ventilation.

els varied between 491–764 ppm with an average value of 584 ppm. It can be seen that CO_2 concentration decreases during nighttime. Variation in concentration was probably caused by occupant activity in the remainder of the house and the decrease during nighttime may be related to reduced activity. For both of the cases, indoor CO_2 levels have never exceeded the threshold level of 1,000 ppm.

Concentrations During Experiments

In the infiltration experiment, 500 grams of dry ice was included in the rooms. A fan was used during the experiment to distribute the emitted CO_2 by the dry ice homogeneously throughout the room. Windows and doors were kept closed throughout the experiment. In this process, the change in the mass of solid dry ice was observed and the increase in the CO_2 level was monitored. Throughout this time, the CO_2 level reached its maximum level, and then it started to decrease gradually. For the first case, the maximum level for CO_2 concentration was recorded as 10,510 ppm, and it took 1 hour to reach this level. After 23 hours of reaching the maximum level, the concentration level was decreased to 457 ppm. During this 24-hour experiment, the average concentration was recorded as 2,925 ppm.

In this experiment, 72% of the measured levels were above the 1,000-ppm threshold. However, after 17 hours and 20 minutes, CO_2 concentration was decreased back to below 1,000 ppm. For the second case, the highest level of CO_2 concentration was recorded as 6,392 ppm, and it took 5 hours to reach this level. After 18 hours and 50 minutes of reaching the highest level, the concentration level was decreased to 531 ppm. The average value was 2,363 ppm. Fifty percent of the measured values were >1,000 ppm threshold level. After 12 hours and 10 minutes, CO_2 concentrations were decreased back to background levels.

In the natural ventilation experiment, 250 grams of dry ice was included in the rooms. Similarly, a fan was used during the experiment to homogenize CO_2 levels throughout the room. The different aspect from the first experiment was that windows were opened when the CO_2 concentration reached its maximum level. This experiment aimed to estimate the effect of opening the windows on the natural ventilation rate. For the first case, the peak level for CO_2 concentration was recorded as 4,537 ppm. After 4 hours and 50 minutes of reaching the highest level, it decreased back to 417 ppm. During this 6-hour experiment, the average concentration was 1,302 ppm, in which 22% of the recorded concentrations were above the threshold level. However, CO_2 concentration levels were decreased back to below 1,000 ppm in just 1 hour and 20 minutes. The highest CO_2 concentration was recorded as 2,453 ppm for the second case. After 4 hours and 40 minutes of reaching the highest level, it was decreased to 372 ppm. The average value was 631 ppm. Nine percent of the measured concentrations were above the threshold level. However, after only 30 minutes, CO_2 concentration levels were decreased back to below 1,000 ppm-level.

Air Exchange Rates

Figure 4 shows the calculated air exchange rates for the two case houses during the infiltration and natural ventilation experiments. The infiltration rate was relatively stable in Experiment-2 in Case-1 at about 0.15 h^{-1}, while it fluctuated in the 2nd house roughly around 0.3 h^{-1}. In Experiment-3, it is seen in the graph that the air exchange rate started to increase when the windows were opened. However, due to concentrations reducing back to background levels relatively quickly, the time was insufficient to observe a stabilized AER, especially for Case-2. In contrast, for Case-1, an AER of 2 h^{-1} could be assumed based on values at 100, 110, and 120th minutes. Both cases show that opening windows had a critical effect on the air exchange rate during the meteorological conditions of the time of the experiments.

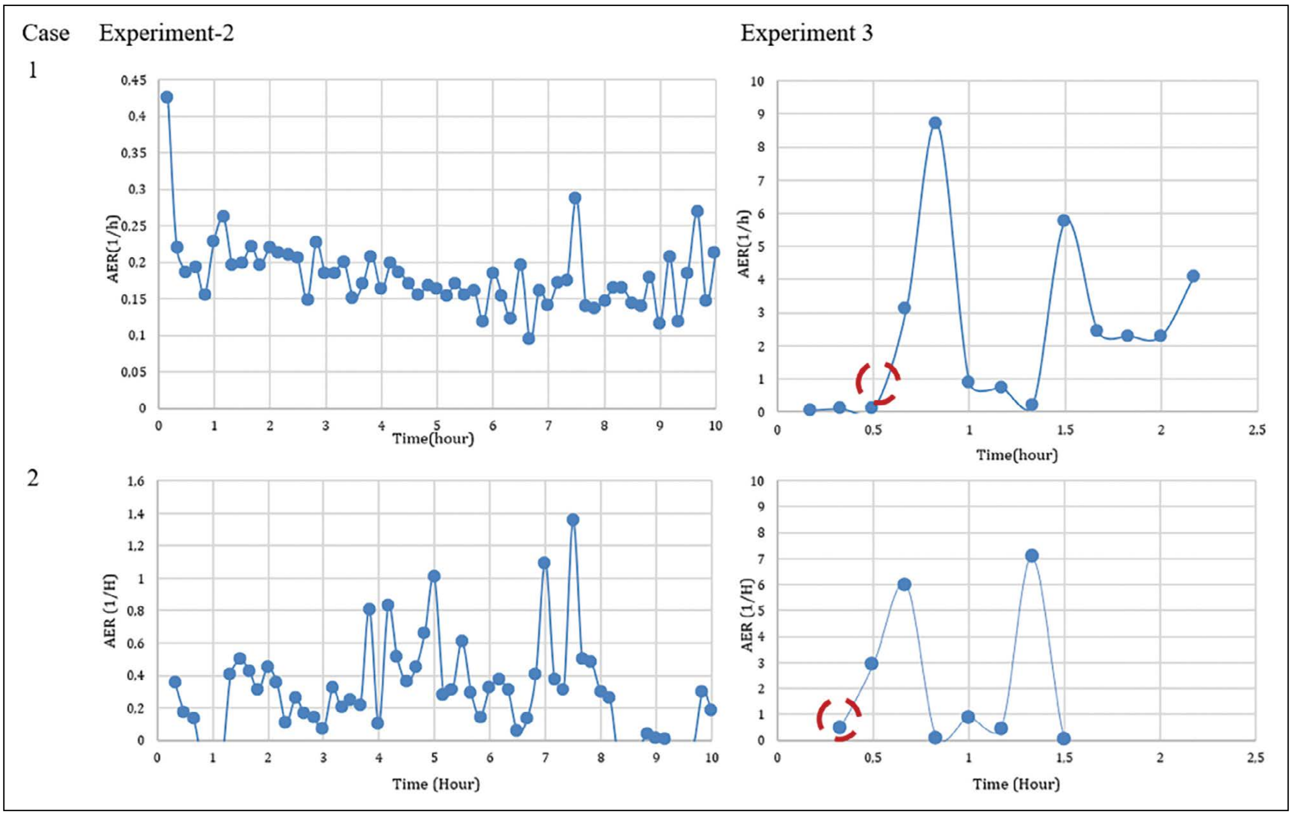

Figure 4. Plot of calculated air exchange rate (AER) values during the experiments.

When the two case houses are compared, it is seen that the maximum CO_2 values in the rooms did not reach the same concentration level, although the same amount of dry ice (500 gr) was used. In the second case, the infiltration rate was higher. This may depend on the height of the house, the number of windows, and the number of leakage areas other than the meteorological conditions outside, e.g., wind speed and direction. The results of the third experiment gave increased natural ventilation by opening the windows. As soon as the windows were opened, we observed sharp changes in the air exchange rate due to increased natural ventilation. While the high CO_2 level in Case 1 fell below 1,000 ppm in 1 hour and 30 minutes, it happened in an hour in Case 2. This shows the effect of increased natural ventilation for both cases compared to low AERs provided by infiltration.

Figure 5 shows the difference between the two case houses' infiltration and windows-open ventilation rates as boxplots. In both cases, estimated ventilation rates were increased considerably by window opening compared to the ventilation provided by infiltration. Many studies monitored CO_2 concentrations in the literature, as shown in Table 3. The literature shows that CO_2 concentration levels can be a useful indicator of the building's overall performance, affecting occupant health [14].

It was reported that CO_2 levels considerably relate to indoor air quality [21]. There is a correlation between indoor CO_2 level, building airtightness, and energy efficiency [16]. In

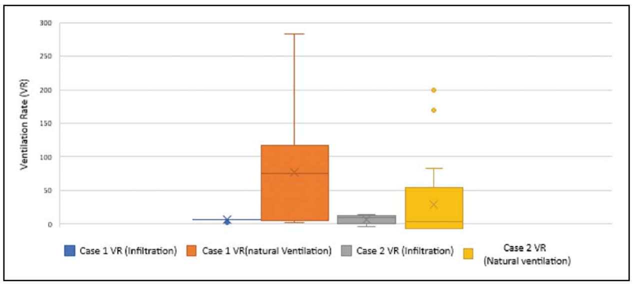

Figure 5. Variation in the estimated ventilation rates.

this study, the indoor CO_2 level was measured to be below the acceptable level of 1,000 ppm (Table 4). In the first and second cases, average indoor CO_2 levels were 479 and 584 ppm. However, these levels were consciously increased to assess the buildings' air exchange and ventilation rates. In the second experiment average air exchange rate was calculated as 0.18 and 0.29 h^{-1} for Case 1 and 2, respectively. The average ventilation rate was 5.9 m^3/h and 8.23 m^3/h for cases 1 and 2. Both of the cases are newly constructed buildings located in the same district of İzmir. However, the second case is located on a higher sea elevation and exposed to an intense wind load, resulting in a higher infiltration potential. According to the results of the second experiment, in the second case, average air exchange rate and ventilation rate due to infiltration was calculated to be higher than the first case. The

Table 3. Comparative literature review

Year	Authors	Location	Building type	Ventilation type	Tools	Findings
2012	Bulut [21]	Undefined	Residential, office, and education building	Natural Natural Natural	Real-time monitoring, numerical methods	The relationship between CO_2 concentrations and other parameters (i.e., temperature, humidity, etc.) is discussed. There found a correlation between CO_2 levels and humidity with particulate matter concentration.
2012	Molloy et al. [15]	Australia	Residential		Real-time monitoring	Energy-efficient designs of newer, more airtight residences can result in high concentrations of pollutants indoors, as they trap pollutants indoors. Therefore, a negative correlation was observed between residential ages and selected indoor air pollutants.
2020	Canha et al. [13]	Portugal	Residential		Real-time monitoring, tracer gas method	Air exchange rates are insufficient to provide good indoor air quality during sleep by reducing the dilution rate of emitted pollutants, even though they are always above the set guideline (0.7 h^{-1}).

Table 4. Comparison of experimental results

Experiment	Data	Case 1	Case 2
Experiment 1	Average background CO_2 (ppm)	479	584
Experiment 2	Average air exchange rate (h^{-1})	0.18	0.29
Experiment 3	Average air exchange rate (h^{-1})	2.36	1.2

third experiment aimed to estimate natural ventilation AER achieved by opening the windows. The average AER was determined as 2.36 h^{-1} and 1.2 h^{-1} while the average ventilation rate was calculated as 76.9 h^{-1} and 34 h^{-1} for cases 1 and 2, respectively. The lower rate estimated for Case-2 than that of Case-1 may have occurred due to not reaching a similar peak concentration before gradual decrease, meteorological conditions, and the window opening area. While the ratio of opening area to volume in 1st case is calculated as 0.085 m^2/m^3, it is calculated as 0.067 m^2/m^3 in the second case. In the second experiment, different levels of CO_2 were obtained despite adding the same amount of dry ice. This was due to the different infiltration levels of the rooms. Since higher CO_2 concentration occurred in the first case, the air exchange rate was lower. This experiment shows the importance of windows on ventilation and indoor air quality. The results of this study are found to be consistent with those reported in the literature. Buildings' air leakage potential, thus infiltration and thermal performance, closely relates to indoor air quality [16]. The literature also clearly concluded that indoor air quality is strongly related to the spread of various diseases through ventilation rate [14]. This study shows that AERs due to infiltration were very low and can be considerably increased when natural ventilation was acquired by opening the windows. Therefore, natural ventilation can play an essential role in maintaining a better indoor air quality and decreasing the risk of virus and disease spread indoors.

CONCLUSIONS

The effect of natural ventilation on reducing the indoor CO_2 concentration is apparent when the two experiments are compared. Factors such as housing type, sea-level elevation, location, window size, airtightness, the number of outdoor facing facades, and window size may determine its rates through infiltration and opening windows. Both case rooms are between the minimum and maximum ventilation rates specified in ASHRAE [11] and contribute to indoor air quality. However, the rates estimated in this study are relatively low and natural ventilation is a result of factors that cannot be controlled by the occupants, which is uncertain to supply a sufficient decrease in the risk of infection spread, e.g., COVID-19.

ACKNOWLEDGMENT

Authors thank Assoc. Prof. Dr. Zeynep Durmuş Arsan and Building Physics Laboratory at İzmir Institute of Technology for the monitoring devices.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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