Experimental Investigation of Indoor Air Quality in an Open Office Environment

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ABSTRACT

Open offices, where more than one person works, have been used frequently in recent years. However, there are many studies on the efficiency of the indoor air quality of the employees in these offices. It has also been shown that the risk of cross-contamination is higher in such offices during the COVID period, but this risk can be reduced by increasing the amount of fresh air. For both efficiency and a healthy working environment, an experimental investigation of indoor air quality (IAQ) according to scenarios was carried out experimentally with the living laboratory created in the R&D center. Working together with 8 engineers in the open office environment investigation was measured with an indoor air quality measuring device at different points throughout the day. With these measurements, both the comfort of the employees was compared and the possible improvements to be made in the devices in order to increase the indoor air quality were examined. According to the results obtained, it was found that suitable conditions in terms of thermal comfort are provided during working hours and the CO_2 level is generally kept below 1000 ppm.

KEYWORDS

HVAC, Indoor air quality (IAQ), Thermal comfort, Sustainability, Energy efficiency

1 INTRODUCTION

Rapid urbanization, ongoing climate changes, and previous epidemic periods such as COVID-19 have highlighted the importance of ensuring suitable indoor air quality (IAQ) in office areas. With employees typically spending more than 80% of their time indoors, IAQ becomes a critical factor in their overall well-being (Marc et al., 2018). The progression of climate change is expected to worsen outdoor air quality due to increasing CO_2 and temperature levels, leading to extreme conditions such as higher indoor temperatures, infiltration of outdoor airborne allergens, and humidity fluctuations (EPA, 2022). Poor IAQ can result in various health issues, including cross-infection, sick-building syndrome (SBS), eye irritation, respiratory illnesses, and allergies (Wojciech et al., 2007; Wyon and Wargocki, 2013), while prolonged exposure can cause up to a 15% decline in office employees' performance (Wargocki and Wyon, 2017). Thus, it is crucial to maintain acceptable IAQ in office environments. To achieve acceptable IAQ in office areas, reducing CO_2 levels through proper ventilation and meeting minimum thermal comfort requirements are essential. Thermal comfort depends on seven factors consisting of air temperature, humidity, radiant temperature, air velocity, metabolic heat rate, clothing, and possible occupant adaptations (Borowski et al., 2022). Recommended measures to provide thermal comfort in office environments include maintaining a temperature range of 20-24°C, a relative humidity range of 30-60% (Sakhare and Ralegaonkar, 2014), and a mean radiant temperature (MRT) range of 18-27°C (Choudhury et al., 2011), along with adequate ventilation. However, ensuring appropriate ventilation is a complex procedure that requires detailed considerations. ANSI/ASHRAE Standard 62.1-2019 recommends a minimum outdoor air rate of 2.5 L/s per occupant at the breathing zone for acceptable IAQ in office spaces (ASHRAE, 2019). Controlling airflow patterns has also been emphasized in a position document (Stewart et al., 2020). In contrast, REHVA published a guideline for post-COVID target ventilation rates, emphasizing the adjustment of outdoor air supply based on indoor CO_2 levels. For health-based ventilation, maintaining a CO_2 setpoint of 550 ppm is recommended, while a setpoint of 650 ppm is suggested for comfort ventilation, resulting in a ventilation rate of 15-25 L/s.person during normal periods (REHVA, 2022). Given the energy consumption of HVAC equipment and the importance of meeting thermal comfort requirements, the potential impacts of these variations in outdoor air rates would obviously be crucial for design considerations. To enhance the precision of design-specific strategies, further studies are required that investigate the indoor air quality (IAQ) of various office environments and ventilation layouts experimentally.

Various experimental studies investigated several optimization strategies of IAQ, thermal comfort and energy for various HVAC applications. Table 1 shows a summary of several related studies. As can be seen, there are various strategies to improve IAQ and thermal comfort rather than directly increasing airflow rates inside the space. Up to 35% energy savings could be achieved by occupancy-based control (OBC) strategy with an acceptable air quality and thermal comfort (Kong et al., 2022). Studies also showed that energy consumption can be reduced by up to 55.8% via demand-controlled ventilation (DCV) strategies without reducing the IAQ (Sun et al., 2011).

Table 1: Several studies from the literature that investigate several strategies to improve IAQ in different indoor environments.

No	Reference	Space Type	Mechanical Applications	Control Strategies	Variable Parameters	Examined Parameters
1	Ming et al. (2023)	Office Meeting Room	4-Way Active Chilled Beam Ventilation	-	- Heat Gains - Terminal Layouts	- Operation Ranges - Contamination Removal Efficiency - Heat Removal Efficiency
2	Wang et al. (2023)	Lecture Room	Radiators & Natural Ventilation	- Occupant-Based Heating and Natural Ventilation Control	- Heat Losses - CO_2 Concentrations	- Thermal Comfort - Energy Consumption
3	Yang et al. (2023)	Office	Personal Heating Devices	-	- Indoor and Ambient Temperatures	- Thermal Comfort Votes - Thermal Sensation Votes - Energy Consumption
4	Tsay et al. (2023)	Office	Fresh Air Heat Recovery Unit (HRU) & Air Conditioner	- Thermal Comfort Control - Energy Savings Control - Productivity Control	- Indoor Temperatures - Air Velocities - Predicted Mean Vote (PMV) - Predicted Percent Dissatisfaction (PPD)	- Thermal Sensation - Thermal Comfort - Air Quality - Energy Savings
5	Kong et al. (2022)	Office	Air Treatment Modules (ATMs) & Dedicated Outdoor Air Handler (DOA)	- Thermal Comfort Control - Energy Savings Control - Productivity Control	- Supply/Return Air Temperatures - Outdoor Air Temperature - Occupancy Rate	- Thermal Sensation - Thermal Comfort - Air Quality - Energy Savings
6	Sun et al. (2011)	Multi-Zone Office Building	Central Air Handling Unit (AHU) With Cooling Coils & Variable Air Volume (VAV)	- CO_2-Based Adaptive Demand Controlled Ventilation	- CO_2 Concentrations	- Energy Consumption

Since the ventilation layout and airflow patterns inside office environments are as much important as the amount of minimum outdoor air supplied, further case-specific studies are required to improve IAQ in a sustainable and economical way. Also, ventilation layouts should be reoriented in a way to provide reduction in the cross-infection risks in office environments without increasing energy demands. In this study, the effects of a different ventilation strategy on IAQ of an open office environment are investigated experimentally. The results obtained from the measurements are evaluated in order to provide some alternatives for the improvement of IAQ inside the office. Also, design considerations for the HVAC&R system design were presented in detail.

2 METHODOLOGY

2.1 Layout of the Selected Office

The selected space is an R&D office, which is located in Ankara, Türkiye and has an open office layout as described in Figure 1. Except for the adjacent spaces shown in Figure 1, all envelopes of the office are open to outdoor environment. The R&D office is planned to be served by a dedicated HVAC&R system, which is separated from the system of adjacent conditioned areas. The office space is located on the attic floor and the structure of the roof did not allow a homogeneous ceiling height. Therefore, suspended ceiling through the long perimeters of the space, which covers the dotted areas presented in Fig. 1, has a clean ceiling height of 2.25 m, and the clean height at the middle area is 2.6 m. U-values of exterior walls, roof and windows were calculated to be 0.23 W/m^{2}K, 0.67 W/m^{2}K, and 2.45 W/m^{2}K, respectively. Although the office was designed for 13 office employees, the office was occupied by 8 people during the measurements, while each occupant was using a laptop along with a monitor. Also, there are 8 LED lights placed to the ceiling, which have 20x20 cm^2 footprint area. The total cooling load caused by the equipment including laptops, monitors and the printer is calculated as 500 W, and the cooling load due to the lighting is assumed to be 10 W/m^2.

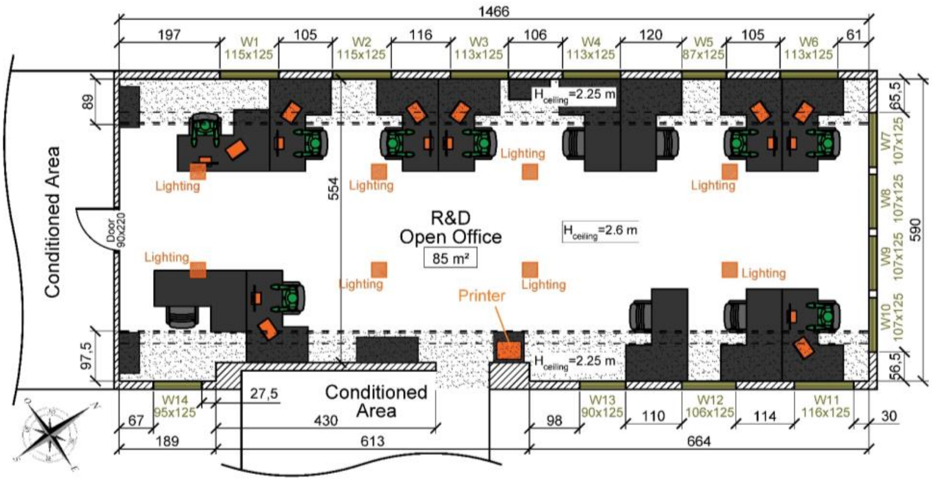


Figure 1: 2D layout of the considered R&D open office.

2.2 Design Calculations and Resulting HVAC&R System

Resulting design data for the considered R&D office were presented in Table 1. For the design of outdoor air and heating-cooling systems, minimum outdoor air rates were determined according to ANSI/ASHRAE 62.1 Standard (ASHRAE, 2019), whereas heating-cooling loads were calculated via Carrier HAP v4.90 software, which utilizes the methodology explained in S. Zaphar (2018). Annual design conditions for the outdoor air were retrieved from ASHRAE

Climatic Design Conditions, which were obtained from Ankara Murted Station as being the closest station to the R&D office. Since return air grills were planned to be located below 2.8 m and the occupancy in that space corresponds to 50% of the total of the ventilation zone, air distribution effectiveness (E_z) and system ventilation efficiency (E_v) were considered to be 0.8 and 0.66, respectively. As a result, required outdoor air rate with 30% safety factor (q_{safe}) was calculated to be 514 m^3/h, whereas design outdoor air rate (q_{design}) was determined to be 600 m^3/h.

Table 2: Design calculations for the HVAC&R system.

Design Conditions		**Outdoor Air Rate**		**Cooling-Heating Load Calculations**				
				Load Source	**Load Details**	**Cooling**		**Heating**
Parameter	**Value**	**Parameter**	**Value**			**Sensible**	**Latent**	**Sensible**
[a]Latitude	40.079 N	[b]q_{occ}	2.5 L/s.person	$Q_{windows}$	18 m^2	2733 W	-	1497 W
[a]Longitude	32.566 E	N_{occ}	13 person	Q_{walls}	48 m^2	80 W	-	369 W
[a]Elevation	843 m	[b]q_{area}	0.3 L/s.m^2	Q_{roof}	84 m^2	1485 W	-	1910 W
Design Heating		Area	85 m^2	$Q_{lighting}$	8 lights	422 W	-	-
[a]DB	-12°C	q_{req}	58 L/s (208.8 m^3/h)	$Q_{equipment}$	8 laptops	500 W	-	-
Setpoint	22°C	[b]E_z	0.8		1 printer			
Design Cooling		[b]E_v	0.66	Q_{occ}	13 people	975 W	780 W	-
[a]DB	31.9°C	[b]q_{calc}	396 m^3/h	Safety	10%	620 W	78 W	378 W
[a]WB	16.8°C			$(Q_{tot})_{space}$	-	6815 W	858 W	4154 W
Setpoint	24°C	q_{safe}	514 m^3/h	$(Q_{tot})_{vent}$	600 m^3/h	976 W		6058 W
		q_{design}	600 m^3/h	Q_{tot}		8649 W		10212 W

[a] The data were retrieved from ASHRAE Climatic Design Conditions website (ASHRAE, 2021).
[b] Values were retrieved from ANSI/ASHRAE Standard 62.1 "Ventilation for Acceptable Indoor Air Quality" (ANSI/ASHRAE, 2019). Minimum air requirements per each occupant (q_{occ}) and per unit area (q_{area}) were obtained by considering the space as an office, whereas the air distribution effectiveness (E_z) and system ventilation efficiency (E_v) were defined by evaluating the ventilation layout described in Figure 1 and Figure 2. The total amount of required outdoor air rate (q_{calc}) was calculated in accordance with the methodology presented in the standard.

The resulting 2D layout of HVAC&R systems and the airflow rates obtained from field measurements are presented in Fig. 2. Accordingly, the outdoor air is provided by UTFP-100 model heat recovery unit (HRU) operating with 100% fresh air. The outdoor air is supplied from 4 swirl diffusers and the air is then exhausted to the HRU from 4 return grills. Each utilized FCU has a heating capacity of 2.2 kW with the usage of 30% ethylene glycol, and there are 4 FCUs placed on the middle region of the suspended ceiling. All FCUs are served by a dedicated heat pump system having a maximum heating capacity of 16 kW. Aside from the literature, outdoor air supply diffusers were located at the middle region, and the return air grills were placed at the lower suspended ceiling. Thermal comfort measurements were carried out at M1, M2 and M3 points shown in Figure 2.

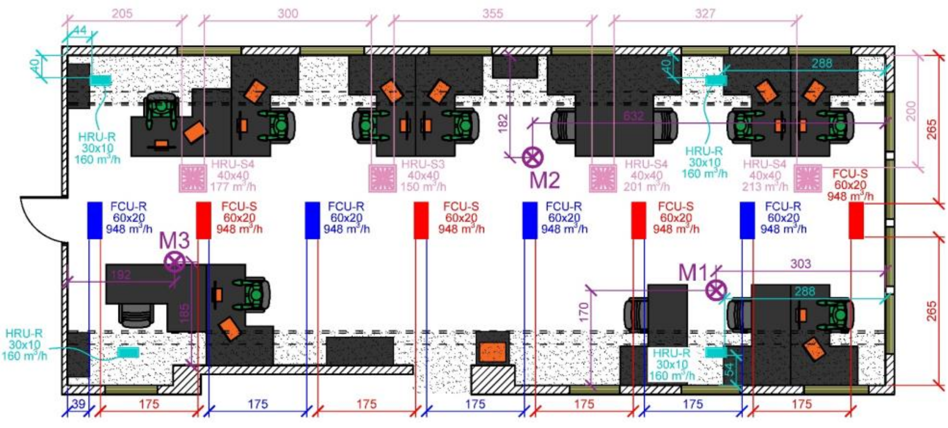


Figure 2: 2D layout of the considered R&D open office.

2.3 Experimental Procedure

IAQ measurements were carried out with Testo® 440 air velocity and IAQ measurement device, which has a turbulence probe (0 - 5 ± 0.03 m/s), CO_2 probe (0 – 10000 ± 50 ppm), humidity-temperature probe (-20…+70 ± 0.5°C, 0-100 ± 2% RH) and a globe thermometer (0-120°C). Measurements were performed for the heights of 1.1 m (represents the breathing zone for sitting and working position) and 1.7 m (represents the breathing zone for standing position) at each location presented in Fig. 2.

3 RESULTS AND DISCUSSION

Measurement data for the location M1 were presented in Fig. 3. The dry bulb temperature increased at 1.7 m from noon. It remained approximately constant at 1.1 m. Although the CO_2 level showed an swinging during office usage hours at 1.7 m, it remained around 600 ppm on average at 1.1 m. PMV and PPD indices were found to be in the range where the space can be considered comfortable. The results of the second and third measurement points showed similar results in terms of thermal comfort. Detailed analysis results are given below.

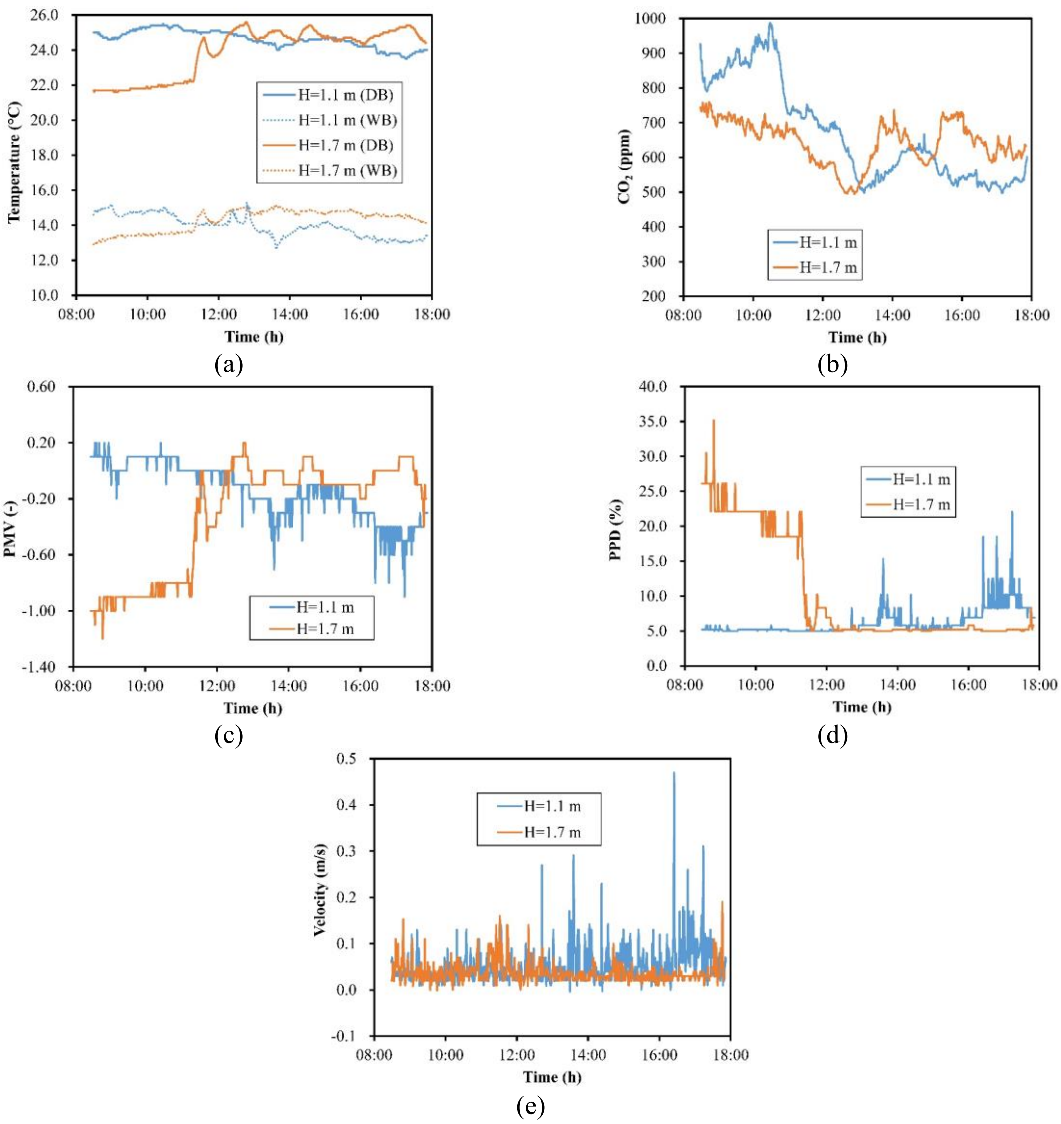


Figure 3. Measurement data from the location M1 against the time period. (a) DB and WB temperatures, (b) CO_2 concentrations, (c) Calculated PMV, (d) Calculated PPD, (e) Air velocity.

Measurement data for the location M2 were presented in Figure 4.

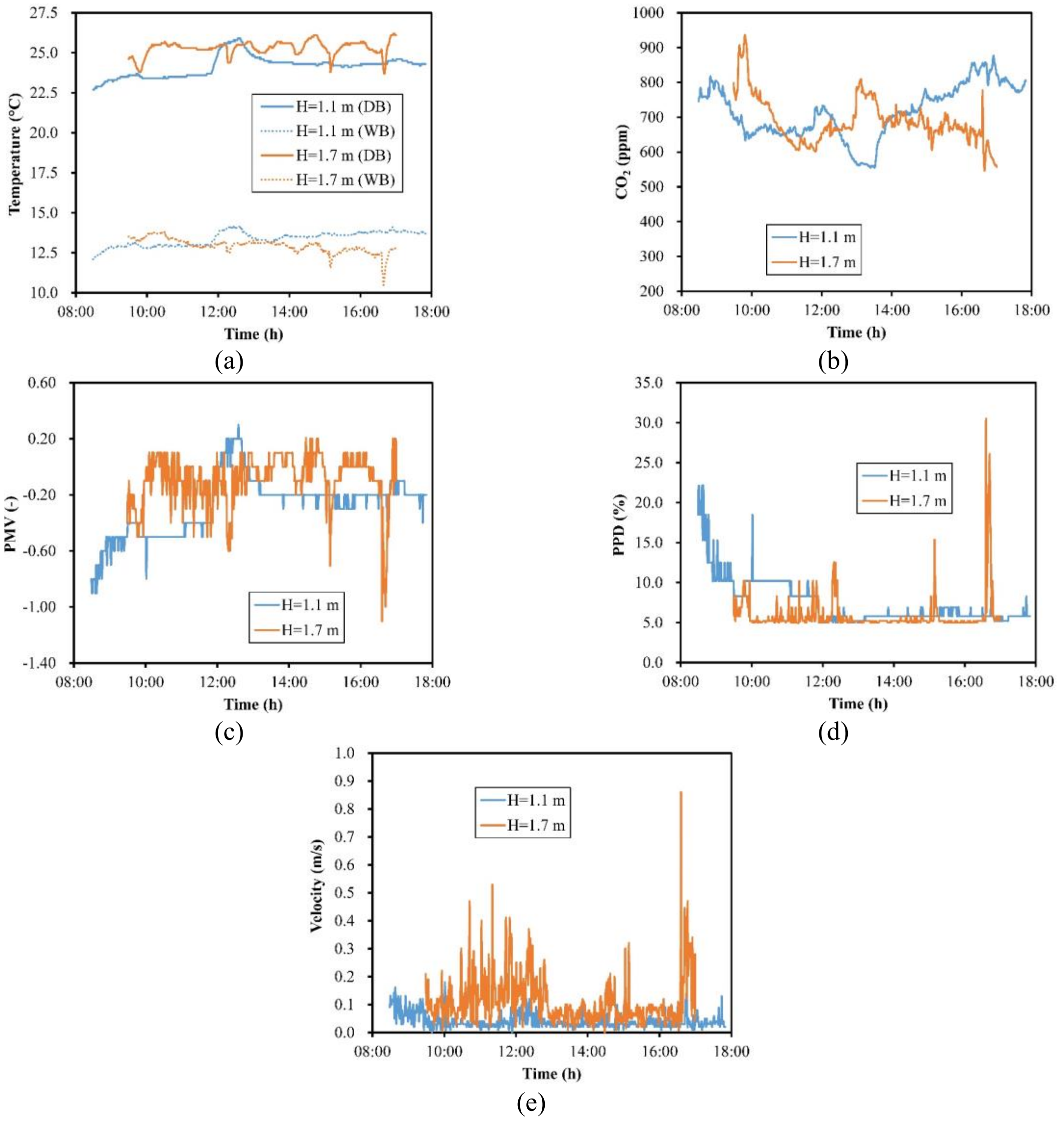
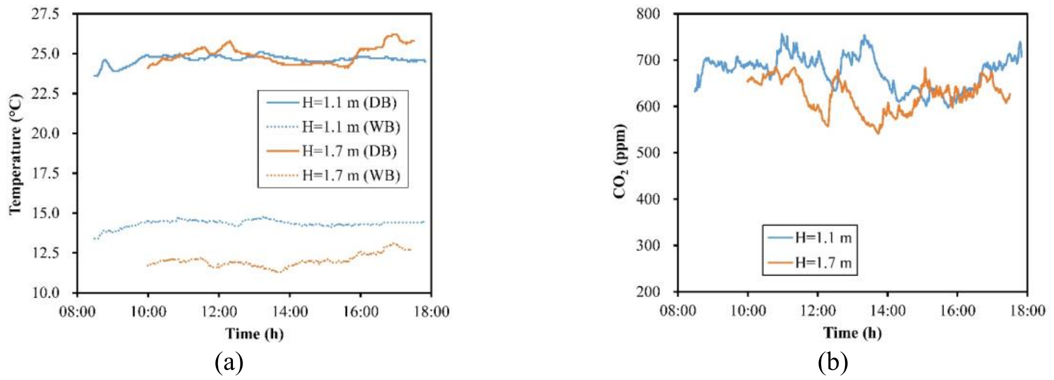
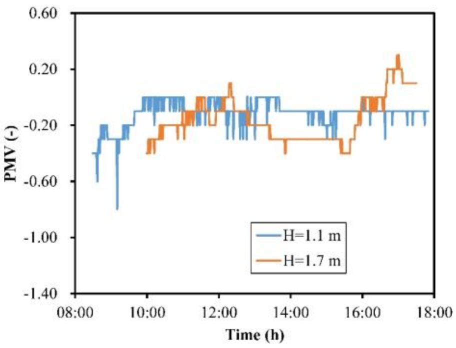


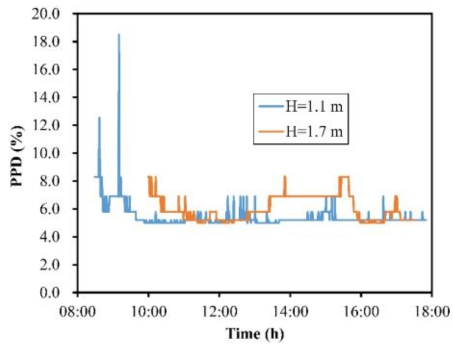
Figure 4. Measurement data from the location M2 against the time period. (a) DB and WB temperatures, (b) CO_2 concentrations, (c) Calculated PMV, (d) Calculated PPD, (e) Air velocity.

Measurement data for the location M3 were presented in Figure 5.

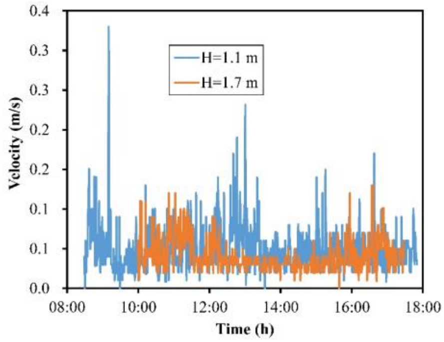




(c)



(d)



(e)

Figure 5. Measurement data from the location M3 against the time period. (a) DB and WB temperatures, (b) CO_2 concentrations, (c) Calculated PMV, (d) Calculated PPD, (e) Air velocity.

4 CONCLUSIONS

The importance of providing thermal comfort in open-plan offices, but choosing options that use energy efficiently and minimize the risk of contamination has come to the fore in the epidemic we live in. CO_2-based ventilation systems and their operating parameters are important in terms of marketing for device manufacturers. In addition, ensuring energy efficiency and determining the options to be offered in the devices should be evaluated within this scope. Ventilative cooling offers an important option in terms of energy efficiency. In the previous study (Birturk and Yilmazoglu, 2022), an annual utilization potential of 59% was determined in Ankara climate conditions. This percentage was found to be 67% for Istanbul and 73% for İzmir. Therefore, from the perspective of the device manufacturer, ventilative cooling should be considered as an important efficiency option for the Turkish HVAC market. For this purpose, studies are continuing to test this option on the date of uploading this text to the submission system (July 2023). Other alternatives to be considered are the humidifier option and improved CO_2-based ventilation.

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