Chan and Ahn *Int. J. Air-Cond. Ref.* (2024) 32:5
https://doi.org/10.1007/s44189-024-00050-2

International Journal of
Air-Conditioning and Refrigeration

RESEARCH **Open Access**

Spatial distribution and transient responses of the thermal environment in an office space equipped with a standing-type air conditioner

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Abstract

Air conditioner (AC) systems are important for maintaining indoor thermal comfort, but discrepancies can exist between setpoints and the actual room temperature. In the present study conducted in a typical Korean office during summer, we identified differences of up to 2.77 °C between the AC setpoint and the average room temperature. This variation may have originated from the oscillatory cooling pattern, leading to moments of discomfort even though the overall thermal balance was maintained. While consistent initial cooling rates were observed for various setpoints, oscillations at 20 °C lowered the efficiency of the AC system. A bi-exponential model applied to the cooling pattern confirmed a two-phase cooling process. Interestingly, the coefficient of performance was highest at the lowest temperature setpoint, even though this led to greater energy consumption and possible overcooling. The weather strongly affected AC performance, with rainy conditions requiring less power than sunny conditions at the same setpoint. Furthermore, our experiment comparing the predicted mean vote (PMV) with actual human comfort revealed that the PMV often recommends a cooler ambient temperature than what occupants actually prefer.

Keywords Air conditioner, Thermal comfort, Predicted mean vote, Coefficient of performance

1 Introduction

The widespread adoption of air conditioners (ACs) has improved the thermal comfort of building occupants in a range of climatic conditions. However, heating, ventilation, and air conditioning (HVAC) systems account for nearly half of a building's energy consumption and around 10–20% of the total energy consumption in developed countries [1]. With the expansion of urban areas and increasing energy demands, HVAC usage and energy consumption are expected to increase further [1, 2].

A central consideration in HVAC system design and operation is the modulation of the cooling and heating capacities, which has direct implications for energy consumption and efficiency. However, in many areas, cooling loads vary temporally and seasonally, and control systems have a significant impact on efficiency [3, 4]. Traditional on/off control methods rely on a thermostat to maintain a predetermined temperature. While simple and initially cost-effective, this approach can result in short-cycling, which reduces the compressor's lifespan and leads to temperature fluctuations [5]. In contrast, variable-speed control systems, which continuously adjust the cooling or heating output, have a higher energy efficiency ratio (EER), more accurate temperature control, and quieter operation [5]. However, these systems have higher upfront and maintenance fees, making them a less attractive option for some users.

AC systems strongly influence thermal comfort in residential and commercial spaces. The predicted mean vote

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(PMV), introduced in 1970 by Fanger [6], is a widely used metric for assessing thermal comfort, especially in AC-controlled spaces [7]. ASHRAE-55 recognizes its significance, noting that a PMV range of −0.5 to 0.5 indicates a thermal environment comfortable for occupants [8, 9]. Despite its widespread use, the model has limitations, thus research has been conducted to improve its accuracy [7].

Outdoor conditions affect not only the performance of AC but also thermal comfort. For example, ISO 7730 specifies different comfort temperatures for summer and winter (24.5 °C and 22 °C, respectively). A deviation of ± 1.5 °C from these temperatures maintains comfort for about 90% of occupants [10]. However, in practical settings, maintaining these temperatures can be challenging. Generally, an AC system relies on the thermostat temperature, which may not be representative of the entire room. This may cause some parts of the room to feel warmer or cooler, leading to potential thermal discomfort for the occupants [9, 11, 12]. Research has shown that precise control over temperature and humidity generally provides better health and comfort outcomes than traditional systems [13].

Various elements of a room can create temperature variations, including electronics, light fixtures, and the occupants. Architectural elements such as windows or large furniture can also impact airflow or create shadow, resulting in temperature differences [14]. Moreover, furniture and walls affect thermal comfort by retaining heat [15]. Thus, simulating the complex interactions between these elements is difficult. While computational fluid dynamics (CFD) simulations can help understand temperature patterns [14, 15], they require realistic boundary conditions to be effective. In dynamic settings such as offices, where conditions change in real time, these simulations may not be accurate. In addition, tools such as TRNSYS have been used to simulate transient effects based on temporal changes in outdoor conditions, but it is still difficult to obtain detailed spatial distributions [16].

Recognizing these challenges, the present study adopted an empirical approach to evaluate the temperature distribution, transient response, coefficient of performance (COP), energy efficiency, and PMV for a typical Korean office during summer. The actual temperature distribution in the cooling space was measured to identify spatial non-uniformity and the difference from the intake temperature, which was used as a control reference. The time response during the initial operation of the AC was then measured according to the set temperature at a representative location obtained from the spatial distribution measurements.

After confirming that a steady state had been reached through transient measurements, the cooling capacity and COP were measured in accordance with the temperature settings in real time. Finally, the spatial distribution of the PMV was measured and compared with the actual thermal comfort felt by the occupants. Through this research, we aimed to provide a holistic understanding of thermal comfort for the design of more effective HVAC system configurations and for the promotion of energy-efficient control strategies.

2 Methodology

The office used for the experiment covered an area of approximately 8 × 6.5 m and had a height of 3 m. This is within the range of a typical educational research facility laboratory in Korea [17]. It was fully furnished and primarily employed for computer-related tasks. The furniture included cabinets and multiple computers used for typical office functions. The office also had blackout curtains, which ensured no external light affected the internal lighting conditions, which were characterized by the bright illumination found in standard office environments. The locations of the AC and the door are indicated in Fig. 1, with the windows situated in Row 0, directly behind the AC. The red boxes represent furniture and the blue boxes denote free space.

A Samsung AP-L2330 standing-type AC was used in the study. The cooling capacity is 6 kW, which is the same capacity used by Kang et al. [18] when analyzing the greenhouse gas reduction effect. The sensors and instruments used in this research are listed in Table 1. They were all calibrated before use.

2.1 Spatial variability in temperature

In our study, we divided the office into a 7 × 9 grid with individual 80 × 80 cm squares to investigate spatial variation in the temperature (Fig. 1). Some of the grid squares were not monitored due to physical obstacles, such as shelves, tables, and other furnishings.

In the experiment, the height of the temperature sensors was maintained at approximately 1.1 m (43 inches) throughout, using a tripod stand. This height was chosen to align with the recommendations of ASHRAE Standard 55. According to this standard, for the assessment of thermal comfort, temperature measurements should be taken at the ankle, waist, and head levels for seated and standing occupants. The specified heights are 0.1, 0.6, and 1.1 m for seated occupants, and 0.1, 1.1, and 1.7 m for standing occupants [8]. The decision to use the 1.1-m height is strategic in capturing relevant data for thermal comfort, particularly focusing on the conditions experienced around the upper body area of occupants.

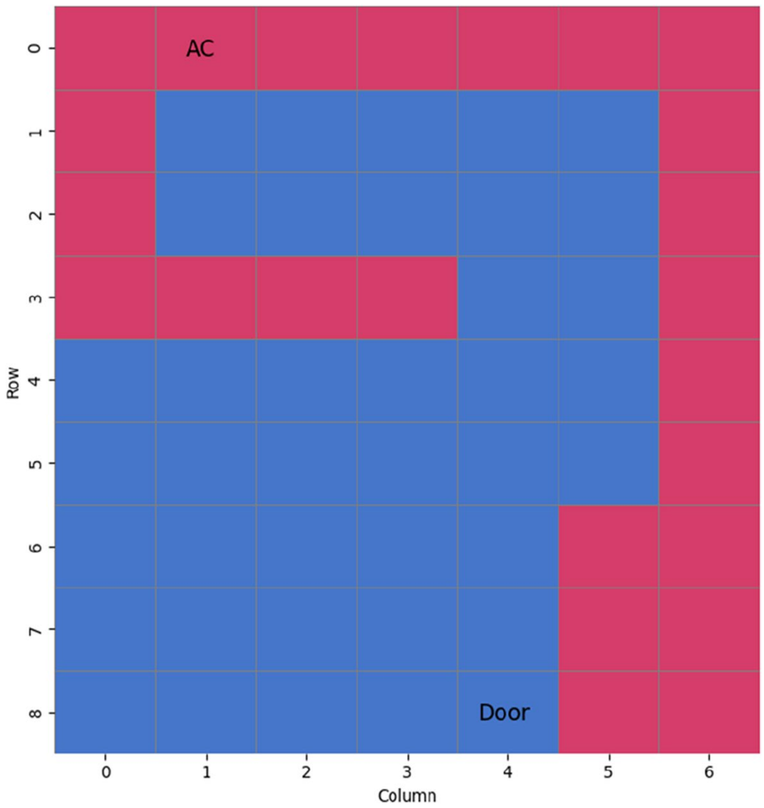


Fig. 1 Overall layout of the office

Table 1 Instruments used for parameter measurements

Instrument	Probe	Measurement	Accuracy
Testo 480	Globe	Radiant heat	± 0.2 °C
	Humidity and temperature	Relative humidity, temperature	± (1.8% RH[a] + 0.7% of mv[b]), ± 0.2 °C
	Comfort	Wind speed	± (0.03 m/s + 4% of mv[b])
Testo 440	Hot wire	Temperature, wind speed	± 0.5 °C ± (0.03 m/s + 5% of mv[b])

[a] *RH* Relative humidity

[b] *mv* Measured value

The temperatures across the grid were recorded for AC settings of 18 °C, 20 °C, and 25 °C. We recorded the temperature under similar outdoor weather conditions for the duration of the study. At each grid location, a sensor was operated for 15 min, and the mean steady-state temperature was recorded. To ensure reliable measurements, we followed a systematic order when taking readings across the grid. These temperature readings were then visualized using a heatmap of the room. We subsequently processed and statistically analyzed the collected data. The mean temperature and standard deviation (SD) were calculated for each AC temperature to assess the thermal uniformity and its potential impact on human comfort.

2.2 AC transient responses

The primary objective of this study was to investigate the transient response of an AC system in a typical Korean office during summer. To achieve this, the room was initially set to a well-defined, non-equilibrium state by turning off the AC unit for several hours before the experiment started. This initial condition allowed for a clear understanding of the transient response of the AC system under different AC settings. The sensor location was selected based on the results from the previous spatial variability experiment to capture the median temperature within the office, thus providing a representative measure of the overall room conditions. The AC unit was programmed to reach two specific target temperatures, 18 °C and 20 °C. For data collection, the sensor recorded environmental data at 5-s intervals to accurately capture transient changes. Each experimental run was conducted over a 2-h period to allow the AC system time to reach its target temperature.

2.3 COP and energy efficiency

The present study also evaluated the COP and energy efficiency of a single-mode AC unit at setpoints of 18 °C, 20 °C, and 22 °C. The office was allowed to reach a steady state for each setpoint before proceeding with the measurements. The inlet and outlet temperatures were recorded at 5-s intervals over a period of 1 h.

The mean air speed (v) was determined by dividing the outlet into 35 equal sections, measuring the speed at each point as shown in Fig. 2 and averaging them. The volume flow rate ($\dot{V}$) can be calculated with the cross-sectional area of the outlet (A) using Eq. (1):

$$\dot{V} = v \times A \tag{1}$$

The Cooling Load (Q_{cooling}) was calculated using Eq. (2):

$$Q_{\text{cooling}} = \rho \times \dot{V} \times C_{p,\text{moist}} \times \Delta T \tag{2}$$

where ρ is the air density, $\dot{V}$ is the volume flow rate, $C_{p,\text{moist}}$ is the specific heat capacity of moist air, and ΔT is the difference in the temperature between the inlet and outlet.

The average cooling load was calculated for the 1-h experimental period. Subsequently, the average COP was determined by dividing the average cooling load by the total power consumption of the AC during the time frame (Eq. 3):

$$\text{COP}_{\text{average}} = \frac{Q_{\text{average}}}{\text{Total Power Consumption}} \tag{3}$$

This experiment aimed to measure both the performance and the energy efficiency of the AC unit under different operating conditions. However, it is important to note that these metrics, while valuable, are not the sole indicators of an effective AC system.

Fig. 2 Segmentation of air conditioner outlet for flow rate measurement

2.4 Influence of weather on AC performance

To examine the effect of the weather conditions on the performance of the AC system, the COP and energy efficiency experiment was conducted again under rainy and sunny weather. Weather forecasts were monitored to select suitable days for each weather condition. Before the experiment, the room was allowed to establish a well-defined, non-equilibrium state, consistent with the previous experiments. Sensors were positioned at the inlet and outlet of the AC.

The A/C system was set to three temperatures: 18 °C, 20 °C, and 22 °C. The temperature, humidity, and power consumption were recorded for a duration of 1 h.

At the start of the experiment, the outdoor weather data was collected. The data collected included specific weather conditions such as temperature and humidity. It is important to note that the sunlight direction was not a significant factor in this study as the office where the experiments were conducted was surrounded by other buildings, which minimized the impact of direct sunlight.

The average COP for each setting was then calculated, enabling a direct comparison of the COP and energy efficiency between rainy and sunny days.

2.5 Actual occupant comfort vs. PMV

The present study assessed human comfort levels under the AC system at different temperature setpoints by capturing both objective and subjective measures of comfort. The experiment was conducted in a typical office during summer. To ensure the objectivity of the data, a sensor was employed to measure the office temperature, relative humidity, and PMV. The location of this sensor was determined based on previous experiments to represent the median room temperature. Before the experiment was conducted, the radiant temperature of the room and the dry bulb temperature were measured for two days and compared with each other.

Participants were required to wear standardized clothing with an insulation of 0.57 clo, which was equivalent to trousers and a short-sleeved shirt [6]. This minimized variation due to different types of clothing. The participants were also instructed to maintain a metabolic rate of

1.0 met, which was achieved by ensuring all participants were seated and in a quiet, relaxed position [6]. Thermal comfort was then assessed using a seven-point scale, which means that there were the same number of options as in the PMV, for which the scores ranged from − 3 to + 3 [6]. At each AC temperature, the participants' thermal comfort levels were assessed using the seven-point scale.

Prior to the start of the experiments, all participants were provided with a comprehensive briefing. This session included an introduction to the study's objectives, detailed instructions on how to use the 7-point thermal sensation scale, and guidance on reporting their comfort levels accurately. This process standardized the understanding of the participants, thereby ensuring the reliability of the subjective thermal comfort data collected during the study.

The PMV values were then computed using the "pmv_ppd" function from the "pythermalcomfort" Python package [19]. The calculation was based on established thermal comfort assessment standards, specifically ISO 7730:2005 and ASHRAE 55–2017. The relevant inputs for the PMV calculation were carefully selected, including an air velocity of 0.1 m/s, a clothing insulation level of 0.57 clo, and a metabolic rate (met) of 1.

3 Results and discussion

3.1 Spatial variability in temperature

The temperature distribution within the office had a spatial variation that could be attributed to the location of the AC unit. Figures 3 and 4 show that the temperature of the room was relatively uniformly distributed when the AC unit was set to 18 °C or 25 °C, with a mean temperature of 20.07 °C and 26.21 °C and an SD of 0.227 and 0.540, respectively. The difference between the mean temperature and the setpoint temperature was thus 2.07 °C and 1.21 °C, respectively.

The low SD indicated that a consistent thermal environment had been established, which was likely to enhance the occupants' thermal comfort. For example, Row 1, which was closer to the AC unit, registered a slightly lower temperature. On the other hand, Row 8, which was close to the office door and furthest from the AC unit was difficult to efficiently cool and thus recorded a higher temperature.

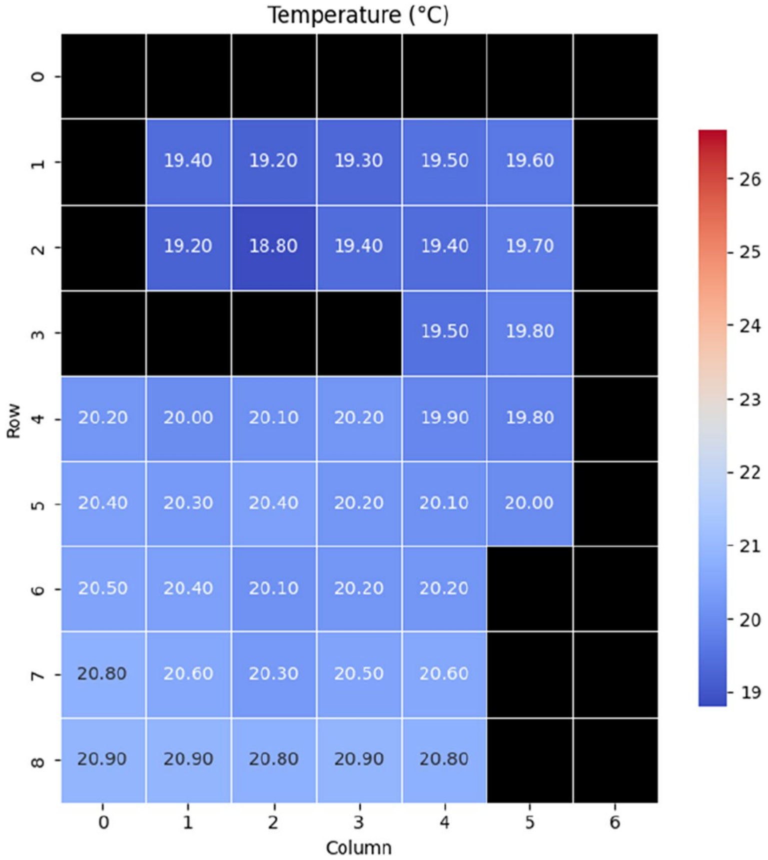


Fig. 3 Office heatmap for the 18 °C setpoint

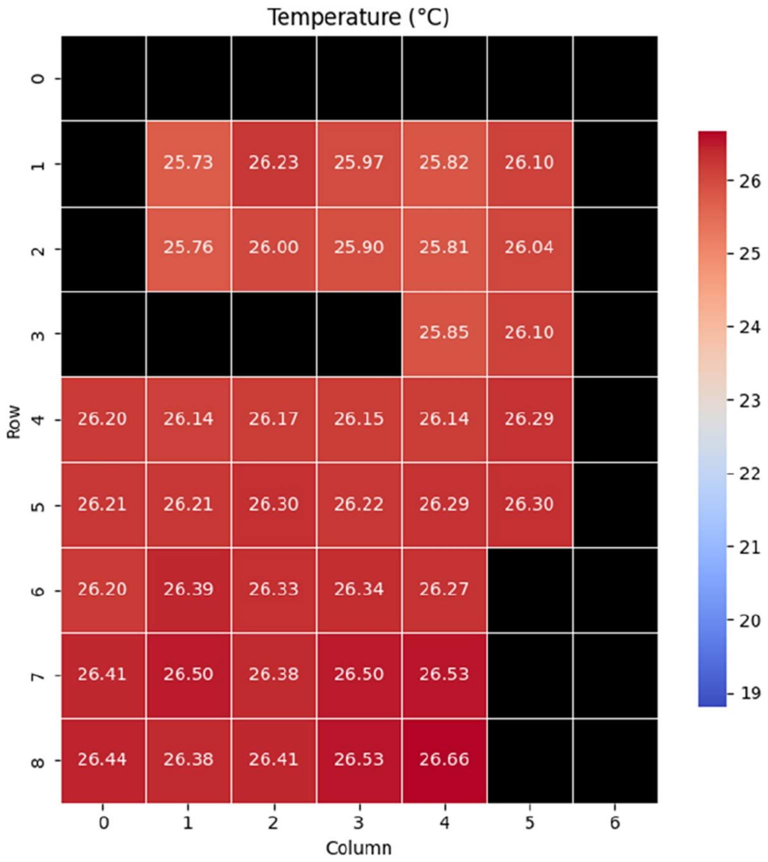


Fig. 4 Office heatmap for the 25 °C setpoint

In contrast, when the AC's setpoint was 20 °C (Fig. 5), the SD of the temperature increased to 0.871, while the mean temperature was 22.77 °C. The difference between the setpoint and actual temperature also increased to 2.77 °C. The higher SD suggests that the 20 °C setpoint may contribute to a less uniform thermal environment, potentially affecting human comfort.

Furthermore, in the observed heatmaps, the minimum temperature zones correlate with areas directly impacted by the airflow from the AC unit. This is consistent with the understanding that direct airflow enhances convective cooling, effectively reducing the temperature more significantly in those regions. As the column and row numbers increase—representing points further away from the AC—the temperature gradually rises. This pattern is indicative of the AC's limited reach, with its cooling capacity attenuating over distance due to air mixing and heat gains from the surrounding environment.

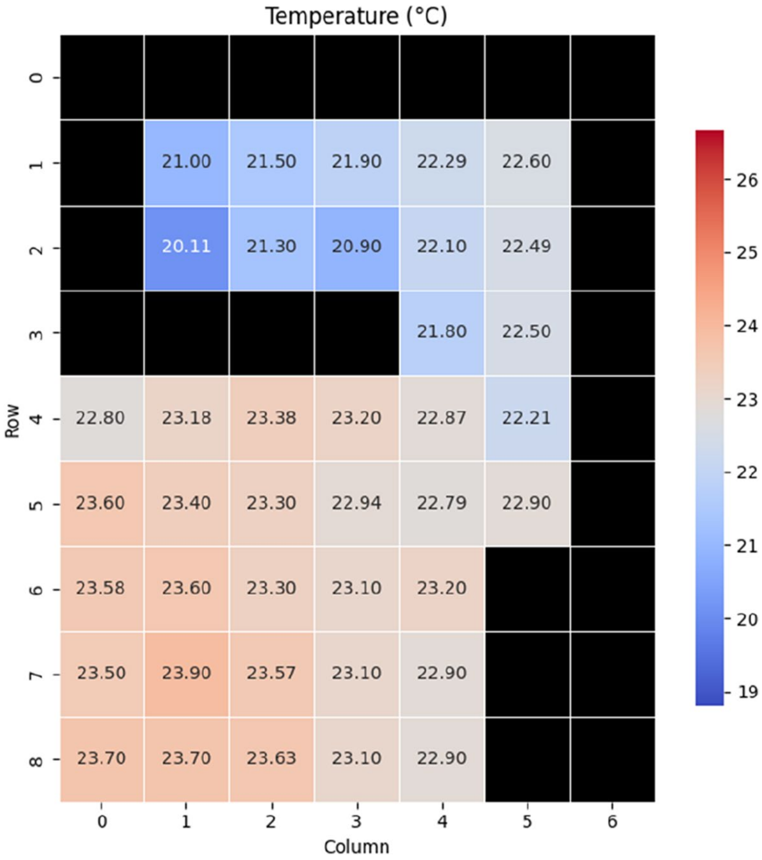
Temperature variation within the same room can cause thermal discomfort for occupants, especially when they move across the office [7]. This variation occurred due to the large size of the office and the presence of obstacles blocking the airflow from the AC. Installing a second AC or optimizing the current placement may address this problem, ensuring improved air circulation and consistent cooling throughout the space.

These findings have important implications for occupant comfort. While a low SD indicates a uniformly cool environment that most occupants would find comfortable, a high SD may lead to localized comfort disparities.

Areas closer to the AC unit could become excessively cool, while spaces further away, such as near the door, may remain inadequately cooled. This non-uniformity could prompt occupants to adjust the thermostat settings more often, potentially leading to increased energy consumption and lower system efficiency.

3.2 AC transient responses

Figure 6 shows that the initial cooling trend for the 18 °C and 20 °C setpoints was similar up to a temperature of 20.3 °C. For the 20 °C setpoint, temperature oscillations began after this point, with a peak-to-peak amplitude fluctuating between 20.3 °C and 21.5 °C, with an average temperature of 20.9 °C. The settling time for this pattern was 47 min. For the 18 °C setpoint, the system did not achieve a steady state within the 2-h



Row	0	1	2	3	4	5	6
0							
1		21.00	21.50	21.90	22.29	22.60	
2		20.11	21.30	20.90	22.10	22.49	
3					21.80	22.50	
4	22.80	23.18	23.38	23.20	22.87	22.21	
5	23.60	23.40	23.30	22.94	22.79	22.90	
6	23.58	23.60	23.30	23.10	23.20		
7	23.50	23.90	23.57	23.10	22.90		
8	23.70	23.70	23.63	23.10	22.90		

Fig. 5 Heatmaps of office for 20 °C setpoint

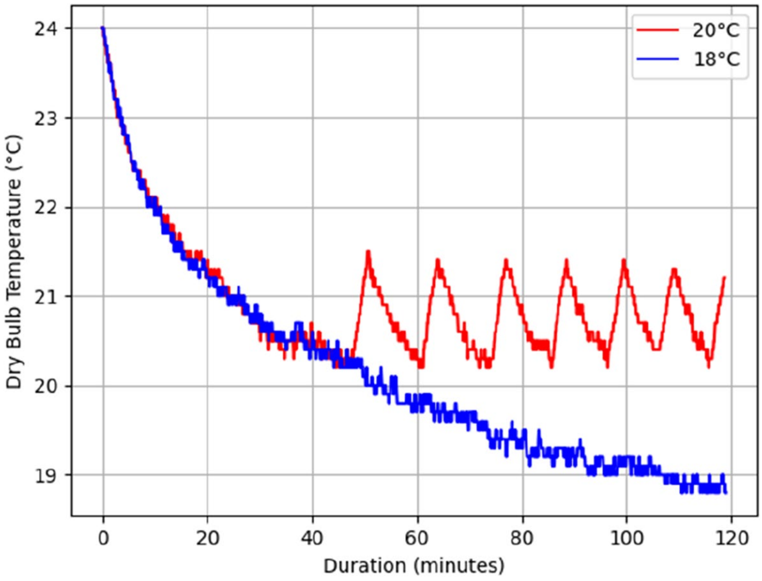


Fig. 6 Transient temperature response for the 20 °C and 18 °C setpoints

period. However, it did reach a minimum temperature of 18.9 °C, which was 0.9 °C above the setpoint. The inability of the AC system to reach the 18 °C setpoint within a 2-h timeframe can be justified by considering thermal inertia and potential air leakage. The office space's materials likely exhibit thermal inertia, absorbing heat and releasing it slowly, thereby delaying the cooling effect of the AC unit. Additionally, air leakage from outside or other areas of the building could introduce warmer air into the space, further impeding the rapid achievement of the desired setpoint. It is conceivable that a longer operating period would allow the AC unit to overcome these challenges and eventually reach the 18 °C setpoint.

However, the similarity in the initial curves suggests that the AC system likely had a consistent cooling rate regardless of the setpoint until it approached the target temperature. This indicates that the system was operating at its maximum cooling capacity during the initial stages for both setpoints. The subsequent oscillations in the cooling likely represented the AC system attempting to maintain the set temperature. However, the peak-to-peak amplitude of 1.2 °C did not comply with ASHRAE-55 2020, which dictates that the peak-to-peak operating temperature difference should not be greater than 1.1 °C during any 15-min period [5].

Our results indicate that a setpoint of 20 °C resulted in more frequent compressor cycling. While this could account for the more significant variance in the office temperature, it also raises concerns about the long-term operational efficiency and maintenance costs of the AC system. Frequent cycling of the compressor can accelerate wear and tear, reducing the system's lifespan and increasing the need for repairs or replacement [2]. This not only impacts comfort but may also raise long-term costs, further complicating the determination of the optimal setting.

Furthermore, the change in temperature over time with a setpoint of 18 °C was used to determine the model that best fitted the temperature pattern (Fig. 7). The curve was first fitted to an exponential decay function as shown in Eq. (4).

$$T(t) = a_1 e^{-t/b_1} + c \tag{4}$$

However, the fit was not satisfactory because it could not capture the entire temperature trajectory, especially in the early stages. This motivated the exploration of a more complex model, with a bi-exponential model employed as shown in Eq. (5).

$$T(t) = a_1 e^{-t/b_1} + a_2 e^{-t/b_2} + c \tag{5}$$

This model included two distinct exponential decay processes, which aligned more closely with the observed

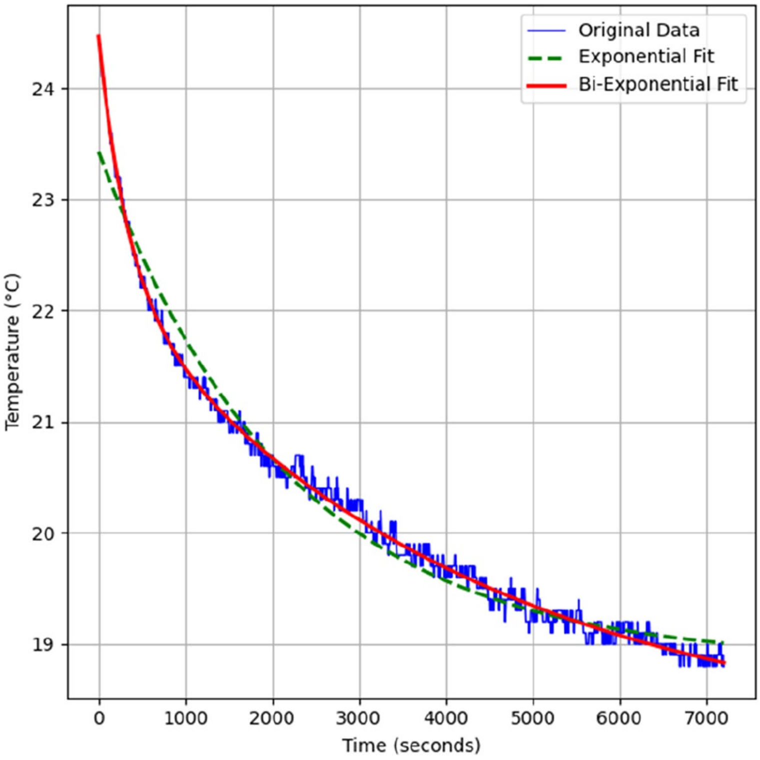


Fig. 7 Temperature decay over time compared with the exponential and bi-exponential models

temperature dynamics over the entire cooling period. This suggests that the room's cooling process had two distinct phases with different decay rates.

Table 2 summarizes the parameters and performance metrics for the exponential and bi-exponential models when fit to the office temperature decay data. The model performance metrics were the coefficient of determination (R^2) and the mean squared error (MSE). R^2 indicates how well the model fits the observed data, with a value of 1 indicating a perfect fit. The exponential model had an R^2 of 0.9764, indicating a good fit. However, the bi-exponential model had a higher R^2 (0.9956), suggesting it more accurately captured the change in the temperature. MSE provided an average of the squared differences between the predicted and observed values. A lower MSE is preferred because this indicates a model that, on average, predicts values that are closer to the observed data. The exponential model had an MSE of 0.0337, while the bi-exponential model had a considerably lower MSE of 0.0062. This supported the superior fit of the bi-exponential model compared to the exponential model.

Based on the ability of a model to accurately predict the drop in temperature, the optimal settings for an AC required to achieve a desired temperature in the shortest time or with the lowest energy consumption can be determined. Furthermore, by modeling different AC settings and their respective power consumption profiles, it is possible to devise an operating algorithm that can rapidly cool a room while ensuring the highest energy efficiency, thus providing a balance between comfort and sustainability.

3.3 Influence of AC settings and outdoor weather

Figure 8 illustrates the wind speed distribution across the AC outlet, divided into 35 sections. Measurements from these sections yielded an average wind speed of 4.38 m/s. The area of the outlet was determined to be $24.5\ \text{cm} \times 42.5\ \text{cm}$, leading to a calculated volume flow rate of $0.4561\ \text{m}^3/\text{s}$. Given that the wind speed remained constant across different AC temperature settings, this volume flow rate has been consistently applied for all temperature setpoints in subsequent analyses.

Figure 9 presents the cooling capacity of the AC system over a period of 60 min for different temperature setpoints during sunny weather. For the 18 °C setpoint (the red line), the cooling capacity exhibited a cyclical pattern, oscillating between approximately 5100 W and 1500 W. The 20 °C setpoint (the blue line), led to more frequent oscillations, fluctuating between 4500 and 1000 W. Interestingly, the 22 °C setpoint (the green line) had noticeably lower peaks between 3000 W and 0. Across all setpoints, the cooling capacity did not remain constant but rather exhibited cyclical behavior, which could be attributed to the on/off cycling of the AC compressor.

When the outdoor weather was rainy, Fig. 10 shows the AC units set at 18 °C and 20 °C exhibited similar oscillating patterns in the cooling capacity. In contrast, when set to 22 °C, the AC exhibited virtually no cooling activity, with only one spike at 55 min.

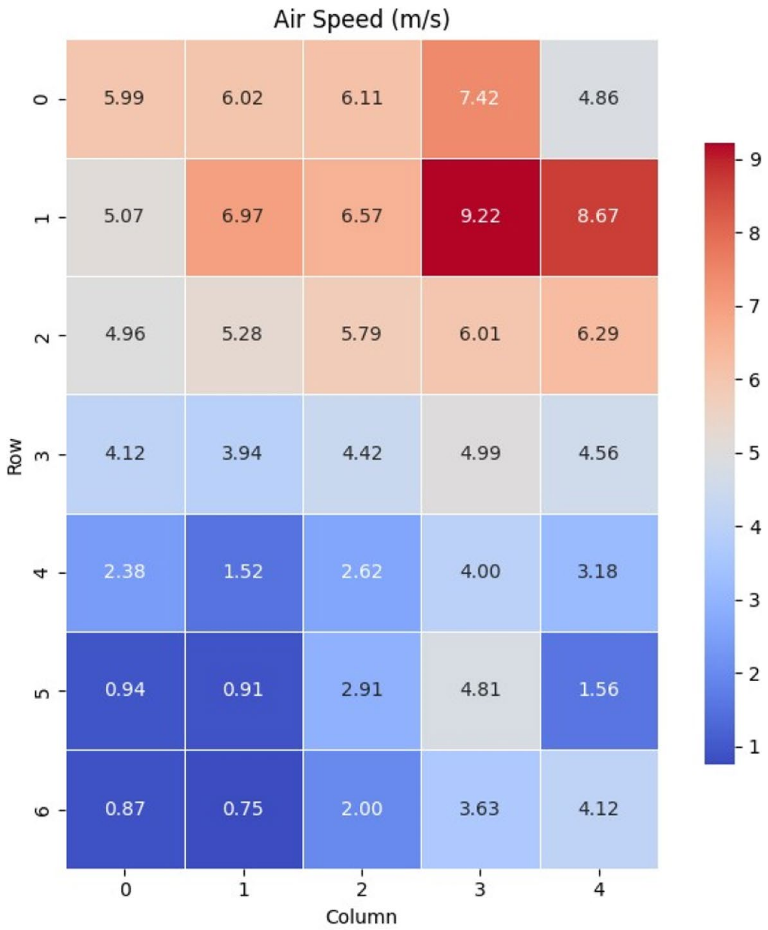
Figures 9 and 10 present both the load and frequency of the AC system's operation. Typically, both factors are crucial to the system's lifetime—frequent cycling can lead to wear and tear on mechanical components, while sustained high loads may cause thermal stress and potential overuse of components. A comprehensive lifetime analysis would require a dedicated study to quantify the effects of these factors and their interactions. Further research could include long-term monitoring to establish a more precise model of system degradation related to load and frequency, potentially leading to predictive maintenance schedules and improved system design.

Table 3 presents the performance of the AC unit for different temperature setpoints and outdoor weather conditions. The power consumption decreased with an increase in the setpoint temperature regardless of the outdoor weather. In sunny conditions, consumption decreased from 1596 W at 18 °C to 443 W at 22 °C. Under rainy conditions, it fell from 1476 W at 18 °C to 226 W at 22 °C. However, in sunny conditions, the AC tended to use more power than in rainy weather at identical setpoints. For example, at 18 °C, the power consumption during sunny days was 1596 W, while on rainy days it was 1476 W. This higher consumption during sunny days was likely due to the additional load from the higher outdoor temperature.

On sunny days, the outdoor temperature was consistently higher (28–29 °C) than on rainy days (20–22 °C). This could explain why the AC unit consumed more power on sunny days compared to rainy days at the same setpoints. The higher outdoor temperature would have resulted in a greater cooling load, requiring the AC unit

Table 2 Comparison of the exponential and bi-exponential models for the decrease in the room temperature

Model	Exponential	Bi-exponential
a_1	4.5889	2.2022
b_1	2178.65	331.35
a_2	0	4.1619
b_2	0	4140.79
c	18.8392	18.1012
R^2	0.9764	0.9956
MSE (°C^2)	0.0337	0.0062



Row	0	1	2	3	4
0	5.99	6.02	6.11	7.42	4.86
1	5.07	6.97	6.57	9.22	8.67
2	4.96	5.28	5.79	6.01	6.29
3	4.12	3.94	4.42	4.99	4.56
4	2.38	1.52	2.62	4.00	3.18
5	0.94	0.91	2.91	4.81	1.56
6	0.87	0.75	2.00	3.63	4.12

Fig. 8 Wind speed distribution across AC outlet

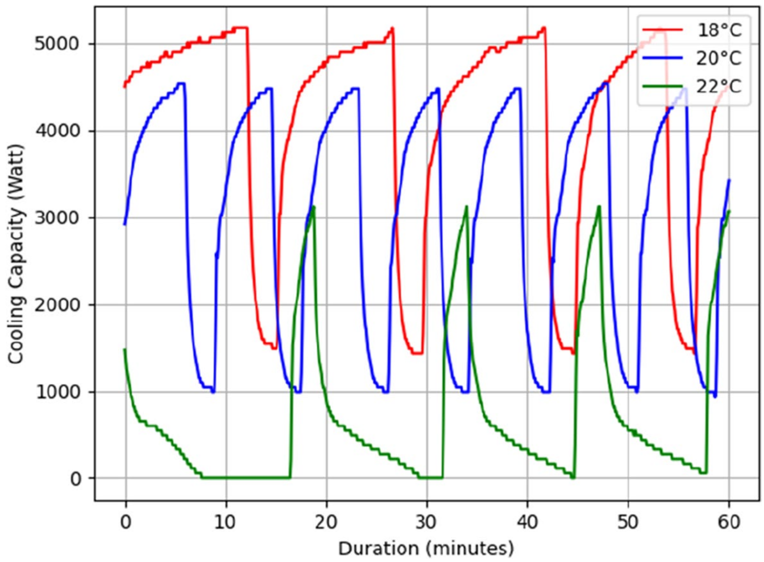


Fig. 9 Cooling capacity over time for various AC settings during sunny weather

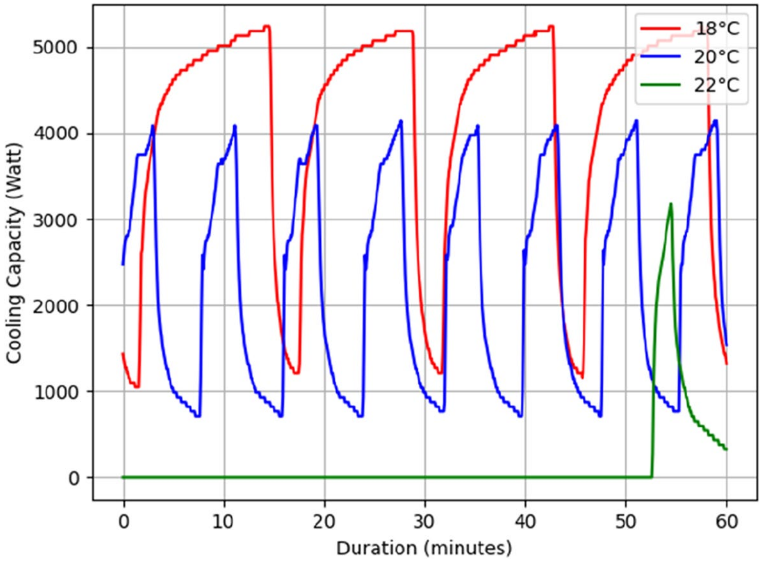


Fig. 10 Cooling capacity over time for various AC settings during rainy weather

to work harder and consume more power to maintain the desired indoor temperature.

Similarly, the outdoor relative humidity was lower on sunny days (66–70%) compared to rainy days (88–94%). Higher humidity levels can increase the latent cooling load, as the AC unit needs to remove more moisture from the air to maintain the desired indoor humidity. However, the influence of humidity on power consumption was not as apparent, primarily because power consumption tended to be higher when the outdoor temperature was elevated, regardless of the humidity level.

Table 3 Performance metrics for the AC unit at various temperature setpoints under different weather conditions

Sunny			
AC setpoint	18 ℃	20 ℃	22 ℃
AC inlet temperature (℃)	19.2 ± 0.5	20.7 ± 0.5	22.6 ± 0.5
Cooling load (W)	4111 ± 367	3035 ± 331	695 ± 226
Power consumption (W)	1596	1337	443
COP	2.58 ± 0.23	2.27 ± 0.25	1.57 ± 0.51
Outdoor Temperature (℃)	28	28	27
Outdoor relative humidity (%)	70	66	66
Rainy			
AC setpoint	18 ℃	20 ℃	22 ℃
AC inlet temperature (℃)	18.8 ± 0.5	20.7 ± 0.5	22.5 ± 0.5
Cooling load (W)	4120 ± 369	2268 ± 310	150 ± 35
Power consumption (W)	1476	915	226
COP	2.79 ± 0.25	2.48 ± 0.34	0.66 ± 0.16
Outdoor Temperature (℃)	22	21	22
Outdoor relative humidity (%)	88	88	94

In addition, an inverse relationship between the setpoint temperature and the mean cooling load was observed. In sunny weather, the cooling load dropped from 4110.95 W at 18 °C to 694.54 W at 22 °C. Similarly, during rainy conditions, it reduced from 4120.03 to 150.18 W when the setpoint was lowered from 18 to 22 °C. This indicates that the AC did not have to exert as much energy to achieve the higher setpoints, a logical outcome given the smaller difference between the desired indoor temperature and the outdoor temperature.

The COP reflects the efficiency of an AC unit, with a higher COP representing higher efficiency. During sunny days, the COP decreased from 2.58 at 18 °C to 1.57 at 22 °C. On rainy days, however, there was a steeper decline from 2.79 at 18 °C to 0.66 at 22 °C. Nevertheless, while a higher COP may indicate efficient cooling, it may not align with individual comfort preferences. Studies have shown that building-related symptoms such as a stuffy nose and a dry throat can occur in office buildings that are too cool. Reducing the cooling of the room to within the thermal comfort guidelines can prevent these occupant symptoms and maintain thermal comfort while conserving energy [19].

Furthermore, the difference in AC performance under different weather conditions raises questions about the adaptability of AC units [20]. Models could be developed to forecast energy costs under different settings, incorporating factors such as local electricity rates, system efficiency, and typical usage hours. These models could then be compared against comfort metrics such as the PMV. This would allow the optimal point at which the system operates at maximum efficiency without compromising the comfort of its occupants to be identified.

3.4 Actual occupant comfort vs. PMV

As shown in Fig. 11, there was a noticeable correlation between the radiant temperature and the dry bulb temperature. Both temperatures fluctuated similarly during the experiment. Given that the radiant temperature affects the thermal sensation of the occupants of a building, its strong association with the dry bulb temperature suggests that the radiant temperature may not provide much additional information. Therefore, in thermal comfort experiments, it could be possible to omit radiant temperature when it closely tracks the dry bulb temperature.

An experiment was designed to assess the relationship between the relative humidity and temperature on both the thermal comfort and the PMV. By assuming that the radiant temperature was the same as the dry bulb temperature and incorporating the uncertainty determined from Monte Carlo simulations with a sampling number of 10,000, we observed the variation in the PMV, with the uncertainty labeled alongside each PMV data point in Fig. 12. These uncertainty values, which arise from the sensor variability presented in Table 1, give an insight into the reliability and variability of the PMV estimates.

Of note was the discrepancy between the actual thermal comfort and the PMV under similar conditions. The PMV data were consistently skewed towards the colder end across all conditions. While PMV values did not reach the positive end of the spectrum for any combination of conditions, the actual thermal comfort readings were mostly zero or a positive value at temperatures higher than 22 °C. According to ASHRAE, PMV values between – 0.5 and 0.5 fall within the zone of comfort, which means that temperatures below 23 °C are uncomfortable [6]. However, this did not align with our observations because participants reported feeling comfortable even at temperatures lower than 24 °C. This can also be seen in Fig. 13. The actual thermal comfort was plotted on a psychrometric chart with the PMV values from – 0.5 to 0.5 shaded in green. It can be observed that the predicted comfort temperature was higher than the actual data collected from the occupants.

Similarly, the ISO 7730 standards set the summer comfort temperature at 24.5 °C ± 1.5 °C, thus establishing a comfort range of 23.0 °C to 26.0 °C, which is anticipated to ensure the comfort of about 90% of building occupants [7]. Interestingly, our data revealed that the participants were comfortable even at a cooler

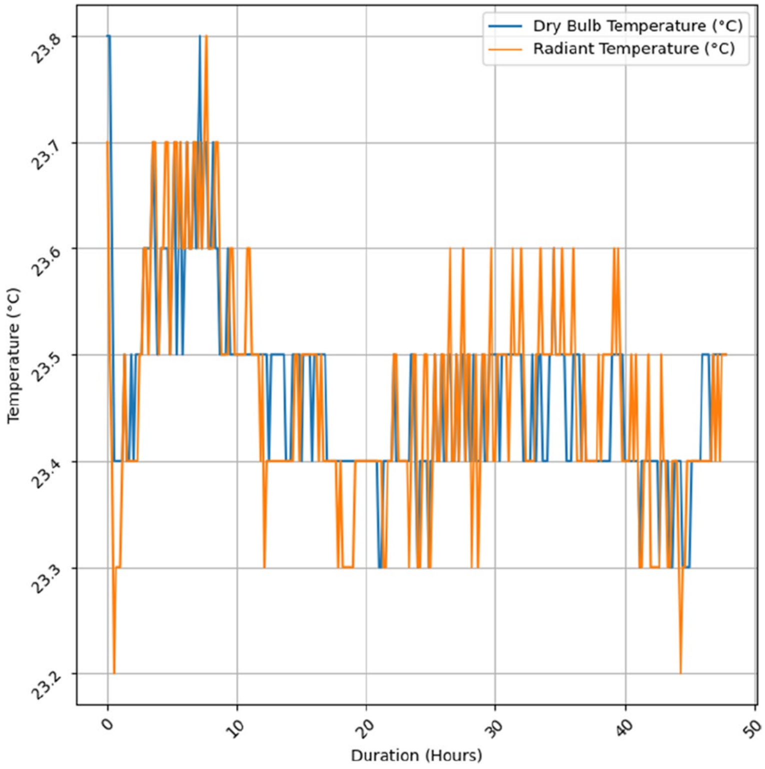


Fig. 11 Dry bulb and radiant temperatures over time

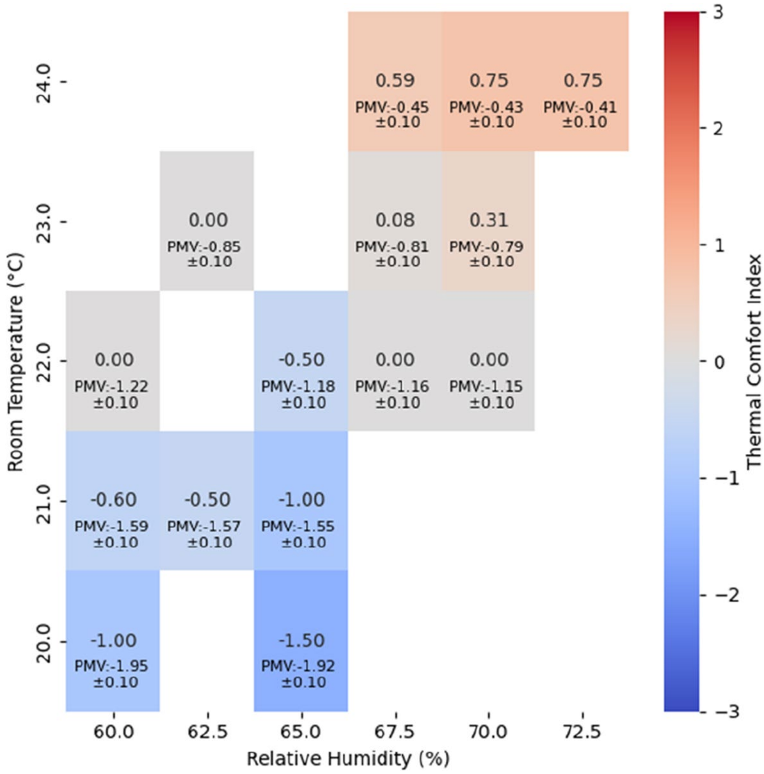


Fig. 12 Heatmap of actual thermal comfort and PMV against room temperature and relative humidity

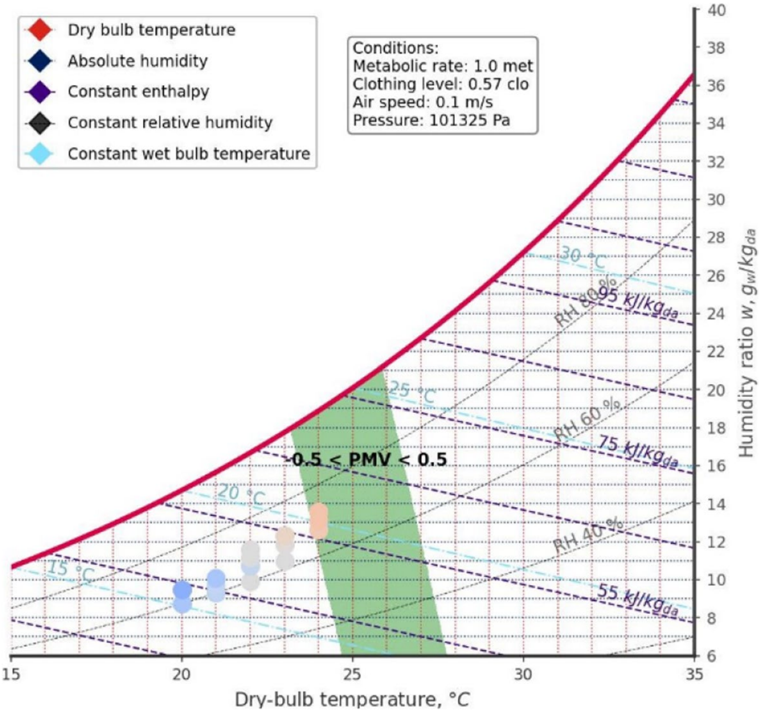


Fig. 13 Thermal comfort visualization with PMV zones in psychrometric chart

temperature of 22 °C, which does not align with the ISO's comfort range. This divergence between our observations and ISO 7730 suggests that actual thermal comfort experiences could be skewed or wider than assumed when compared to standardized guidelines.

In summary, the experiment revealed that both actual thermal comfort and the PMV moved towards values indicating less comfort as the temperature fell. However, the correlation between these two measures was not perfect. Nevertheless, it is important to note that this was a small-scale experiment with limited data points. For a more comprehensive understanding and validation of these findings, broader research in the future is needed.

The PMV in its current form provides broad predictions of thermal comfort, but actual human comfort perception may require more detailed metrics.

4 Conclusions

The present study provided a comprehensive analysis of an AC system within a typical Korean office during summer. We found that the uniformity of temperature distributions across the office varied significantly based on the AC setpoints. Specifically, while settings of 18 °C and 25 °C led to more consistent cooling across the office, the 20 °C setting resulted in uneven temperature zones. This emphasizes the importance of carefully selecting AC settings to ensure consistent thermal comfort.

Further, we observed that the initial cooling rates of the AC system remained consistent across different temperature setpoints. However, the oscillations observed for the 20 °C setpoint raised concerns about compliance and the system's long-term efficiency. In addition, the bi-exponential model proved superior in capturing the temperature decay dynamics, suggesting a two-phased cooling process.

The study also identified variations in AC power consumption based on external weather conditions. On sunny days, the AC system experienced higher power consumption, which was attributed to the higher external temperatures and radiant heat. In addition, while a lower AC setpoint led to a higher COP, it may result in overcooling and occupants may suffer from thermal discomfort.

There was also an observed discrepancy between the standardized thermal comfort metric PMV and actual human comfort experiences. While PMV offers broad thermal comfort guidelines, our research indicates that individual perceptions can differ significantly from these standards. This suggests that there is a need for more adaptive approaches to thermal comfort that prioritize individual experiences over universal metrics.

Acknowledgements
This work was supported by the Korea Institute of Energy Technology Evaluation and Planning (KETEP) and the Ministry of Trade, Industry & Energy (MOTIE) of the Republic of Korea (No. 20212020800070).

Authors' contributions
The authors have read and approved the final manuscript.

Availability of data and materials
Data are available upon request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 7 January 2024 Accepted: 1 February 2024

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