Wind Engineering Joint Usage/Research Center
FY2024 Research Result Report

Research Field: Indoor Environment
Research Year: FY2024
Research Number: 24242008
Research Theme: Research on transient contaminant transport prediction and personalized ventilation strategy in non-uniform environments with unsteady flow

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Budget [FY2024]: 340,000 Yen

*There is no limitation of the number of pages of this report.
*Figures can be included to the report and they can also be colored.
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1. Research Aim

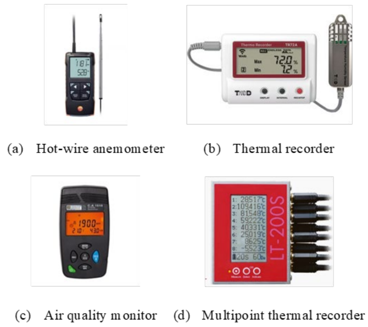
In public building spaces, creating personalized non-uniform environments is conducive to reducing the spread of pollutants, enhancing occupant comfort, and ultimately improving the quality of life while reducing energy consumption. However, there are many challenges in developing non-uniform environments tailored to individual needs. These challenges include how to efficiently predict indoor distribution data based on limited data, how to formulate clear control strategies for complex and varied personalized demands, and how to quickly track indoor particles to regulate and reduce transmission risks. We have conducted research on non-uniform environments from multiple perspectives. On one hand, prediction models that combine computational fluid dynamics (CFD) and Markov chain technology have received widespread attention in the field of pollutant prediction. In our past research, we proposed a Markov chain model based on non-uniform states. This model divides Markov chain states based on both flow field velocity and spatial dimensions, thereby improving prediction accuracy by reducing velocity differences within divided states. We aim for the model to be applicable for rapid pollutant prediction in dynamic ventilation scenarios. However, the significant cost associated with redefining states and recalculating transition matrices for dynamic ventilation poses a challenge. To address this, we propose a method based on clustering and flow field partition frequency to determine non-uniform states. Further verification and discussion are needed regarding the cost and accuracy of this method in dynamic calculations. On the other hand, in non-uniform ventilation systems, the optimal ventilation scheme may not align well with user preferences. Given the diverse characteristics of user needs, it is meaningful to optimize ventilation design through personalized recommendation methods. The study recruited experimenters to participate in the subjective thermal response experiment in a dynamic ventilation environment and extracted the differences between the subjective and the objective. Result aims to provide quantitative references for evaluating indoor dynamic environments in terms of health and comfort.

2. Research Method

This study investigates the impacts of variable dynamic ventilation environments formed by dynamically adjusting supply air flow elements on human real - time perception, comfort, and satisfaction through conducting human - subject experiments in a modified artificial climate chamber. The goal is to provide valuable insights for refined environmental control based on user needs.

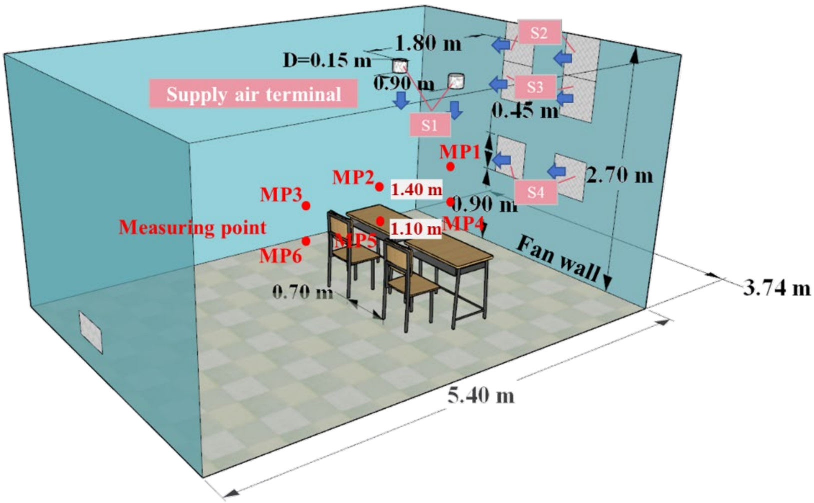
Three conditions of variable dynamic ventilation environments were designed for the experiments, involving variations in supply air outlet position, supply air angle, supply air waveform type. The experiments were carried out from May to June 2024, with a total of 18 student subjects recruited.

Four types of measurement instruments were used. They were employed to measure the wind speed, temperature, and carbon dioxide concentration at 6 fixed measurement points in the room, as well as the skin temperature at 8 parts of the human body. As shown in the experimental flow chart, each operating condition experiment lasted for 1 hour, and the supply air factors were adjusted every 20 minutes. During this period, the students' skin temperatures were continuously recorded. Before and after each adjustment, subjective questionnaire surveys were conducted 8 times at unequal intervals, covering aspects such as Thermal Sensation Vote (TSV), Thermal Comfort Vote (TCV), satisfaction (Thermal Satisfaction - TS, Air movement Satisfaction - AS), and preference (Thermal Preference - TP, Air movement Preference - AP).

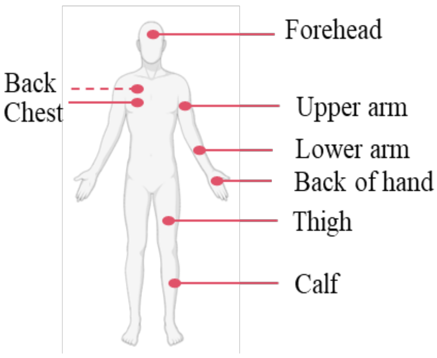


(a) Experimental instrument

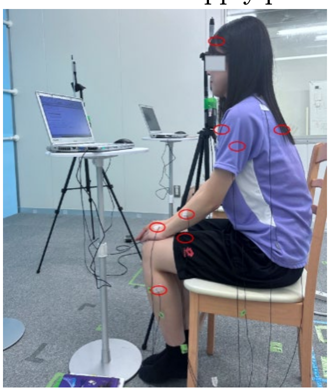
(b) Photos of subjects participating in experiments



(c) Layout of the chamber configured with different air supply ports



(d) Eight measuring body segments



(e) Photos of subjects wearing temperature sensors

Figure 1 Methods

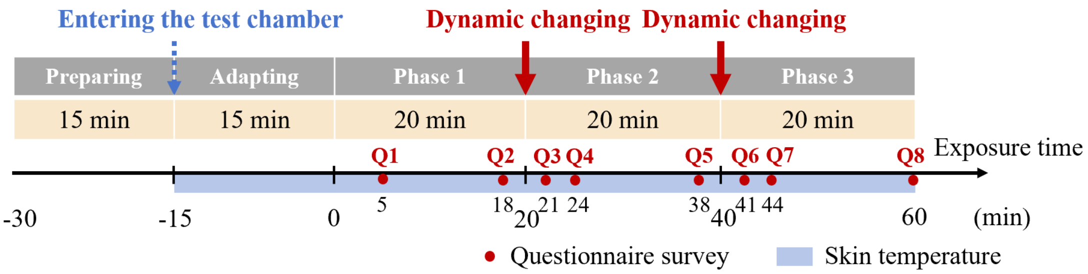


Figure 2 Experimental procedure

Table 1 Experimental conditions for different controllable factors

Case no.	Controllable factor	Order of dynamic change (Phase 1–Phase 2–Phase 3)	Supply air terminal no.
1	Air supply position	Top air supply (S1)–side air supply (S3)–middle air supply (S4)	S1, S3, S4
2	Air supply angle	Up 45°–Horizontal–Down 45°	S2
3	Waveform of supply airflow	Sine wave (T = 200 s, AVG = 0.25 m/s, A = 0.05 m/s)–constant–rectangular wave (T = 200 s, AVG = 0.25 m/s, A = 0.05 m/s)	S3

3. Research Result

3.1 Physical environments

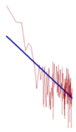
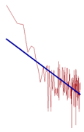
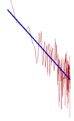
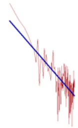
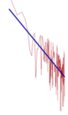
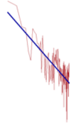
Air velocity in the occupied zone showed a significant change. Especially when the air supply angle changed and air was directed toward the workspace, the velocity increased from 0.052 m/s to 0.14 m/s. In Case 3, although the supply airflow patterns included sinusoidal and rectangular wave forms, they shared the same average value and amplitude, resulting in approximately equal average wind speeds measured. Since the cooling capacity introduced into the room by the supply air was identical, temperature variations under the three dynamic air supply controls were minimal, within 0.2 °C.

To quantify the airflow fluctuation characteristics of VDVC, the analysis focused on two key time points around dynamic switching adjustments, namely before and after 20 minutes (18-22 minutes) and before and after 40 minutes (38-42 minutes). These characteristics were collectively characterized using turbulence intensity (TI), velocity power spectrum, power spectral exponent of velocity (β_v), and time-averaged relative velocity difference. The results are presented in Table 2. According to the TI analysis, three dynamic control strategies enhanced airflow fluctuations, resulting in high TI values (>20%). Adjustments in the air supply angle and waveform induced more significant fluctuation intensities, with the waveform adjustment exhibiting the highest initial fluctuation intensity, reaching 38.6%.

From the frequency domain perspective, power spectral exponent of velocity (β_v) reflects the frequency distribution of velocity fluctuations. Under the case where the air supply position was changed, β_v was lower than in the other two cases. Notably, β_v was particularly small, 0.527, during the second change in position, approaching the value (0-0.5) reported for constant wind in previous studies. From the perspective of ensuring human comfort, β_v for dynamically simulated natural wind should ideally be as large as possible. The β_v values observed under the other two cases align with levels approximating natural wind.

The measurement heights (1.10m-1.40m) encompasses the vertical microenvironment covering both the thermally sensitive zone above the seated level and the breathing zone. Excessive dynamic differences within this range may impair vertical airflow uniformity. The results indicated that the sinusoidal-constant phase exhibited the most pronounced TA$^{\Delta u_{rel}(t)}$, reaching 56.9%. Analysis of the power spectra further reveals that waveform adjustment led to a correlated enhancement of adverse vertical differences and high-frequency fluctuations. In contrast, adjustment of the air supply vent position primarily altered the spatial distribution of airflow, resulting in a flow field characterized by lower fluctuations and greater relative stability.

Table 2 Air movement parameters under different conditions

	Case 1: Position		**Case 2:Angle**		**Case 3:Waveform**	
	1st switching: 18-22min	2nd switching: 38-42min	1st switching: 18-22min	2nd switching: 38-42min	1st switching: 18-22min	2nd switching: 38-42min
TI (%)	27.4%	22.5%	35.2%	33.0%	38.6%	31.1%
Power spectrum of velocity						
β_v	1.068	0.527	1.287	1.374	1.369	1.293
TA$\Delta u_{rel}(t)$	36.9%	29.3%	28.0%	34.5%	56.9%	24.2%

3.2 Skin temperature

We tested local and whole-body skin temperature changes by selecting four representative body sites—forehead, lower arm, back of hand, and calf—vertically distributed and exposed without clothing coverage. Using the criterion that local skin temperature changes (ΔTsk) exceeding ±0.5°C affect thermal comfort, we found: skin temperature decreased gradually from the upper to lower body, with the forehead showing the highest and most stable temperature (about 35.0°C); Only the calf experienced mild discomfort under VDVC (with fluctuations in Case 1 and Case 3); Despite VDVC successfully creating a non-uniform airflow environment through supply air parameter adjustments, overall skin temperatures did not change significantly, and the Mean Skin Temperature (MST), as shown in Figure 3, remained stable throughout parameter variations (maximum fluctuation: 0.30°C, within the normal range of whole-body thermal fluctuations), indicating no impact on thermal comfort.

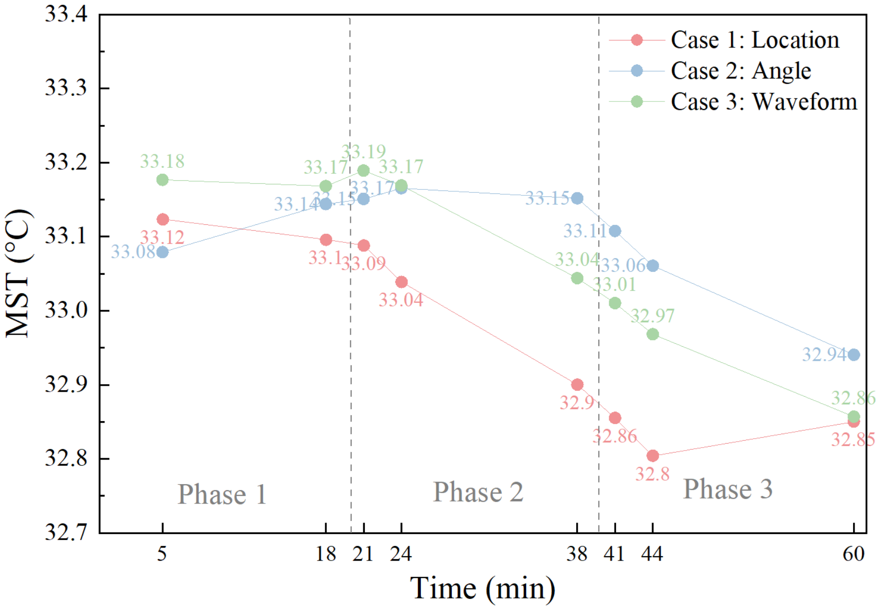
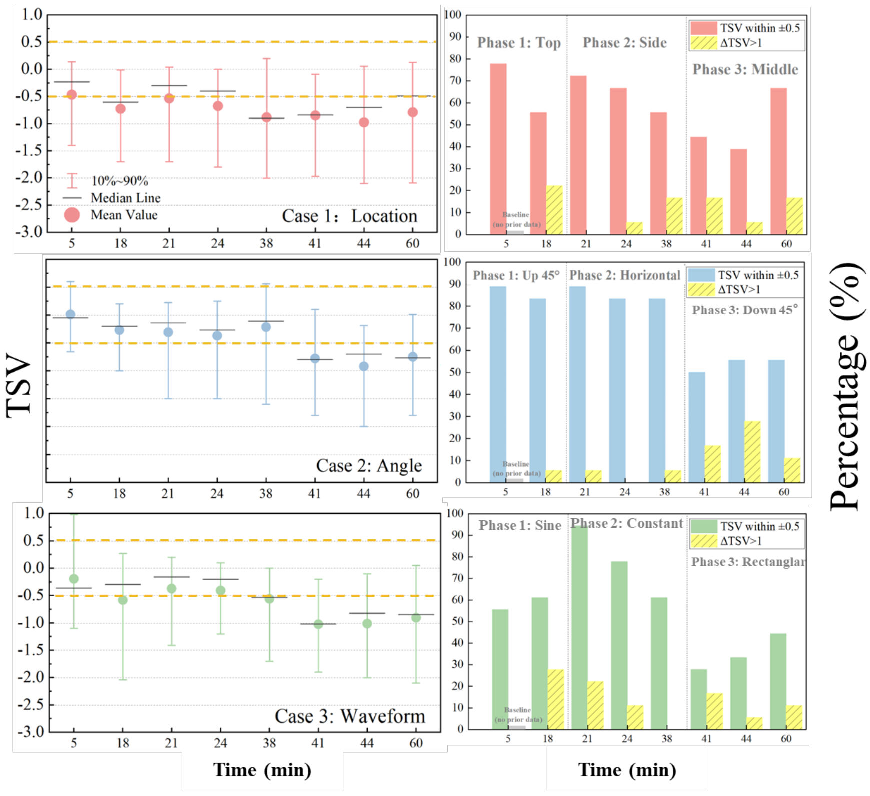


Figure 3 MST changes in the experiments

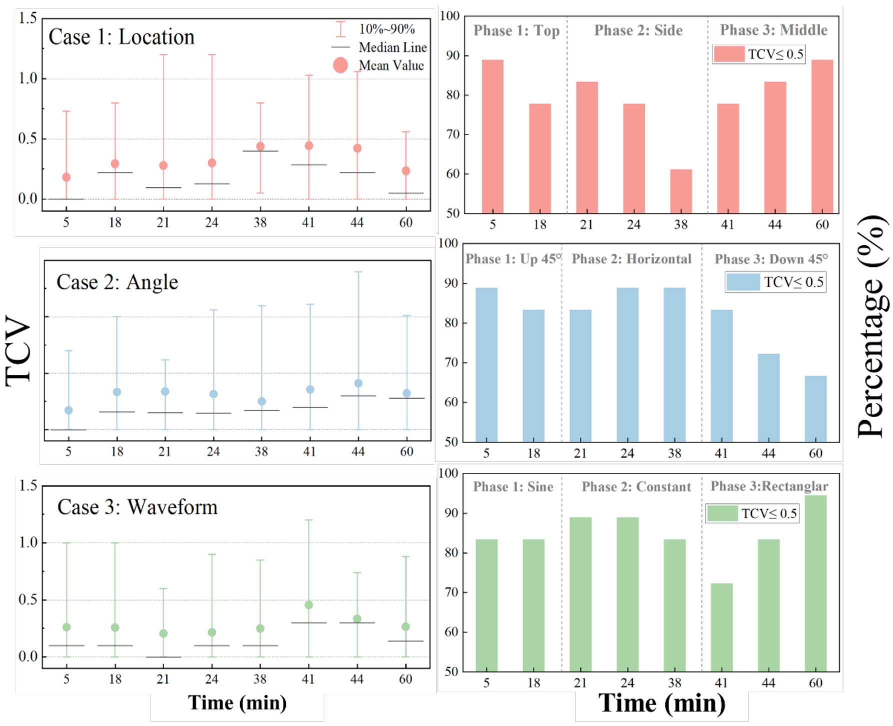
3.3 Subjective survey feedback

Figure 4 presents the variations in TSV, with the yellow-shaded area representing the neutral thermal range (±0.5). As shown in Figure 4(a), none of the test conditions remained within the ±0.5 range throughout the entire experiment, indicating that the thermal sensation of the participants fluctuated in response to the dynamic ventilation controls. Compared to the relatively stable MST shown in Figure 6, subjective perceptions exhibited greater variability than individual skin temperature differences. In Case 1 (supply air location modulation), transitioning from top to side air supply increased TSV by approximately 0.2 units, followed by three consecutive decreases, reaching as low as -0.89. During the middle air supply phase, TSV remained stable between -1.0 and -0.8. Under Case 2 (supply air angle modulation), downward airflow, directed more intensely at the occupied zone, induced a slight cold sensation. Conversely, other phases maintained TSV values closer to neutral. In Case 3-waveform, with sinusoidal airflow, TSV decreased from -0.20, though it remained within the comfort zone. When the flow shifted to constant airflow, TSV initially rose but subsequently returned to approximately -0.55. Notably, switching to square-wave airflow triggered a significant drop in TSV, reaching as low as -1.

Building upon the mean value analysis, this study further examined occupant thermal responses through a proportional distribution of individual thermal perceptions. The right-hand histogram in Figure 4 presents two key indicators: 1) the proportion of participants reporting neutral thermal sensation (TSV within ±0.5) and 2) the dynamic perception ratio (highlighted in yellow), representing participants experiencing TSV shifts exceeding 1.0 unit between consecutive time points, reflecting the perceptual intensity of airflow interventions. The first time point serves as the baseline (gray-marked). In Case 1, top and side air supply configurations achieved identical neutral responses (55%). During mid-level supply transitions, the percentage of neutral TSV followed the trend of mean values, initially decreasing and then recovering. At the 18-min mark, 22% of participants reported cold sensation shifts. Top-to-side supply transitions yielded a 0% dynamic perception ratio, indicating small intervention, although this ratio increased with time. Conversely, mid-level supply transitions caused 16% cold shifts, which later stabilized. In Case 2, supply air angle modulation maintained the highest neutrality proportions (TSV ± 0.5) among all cases. Horizontal and upward airflows maintained TSVs within the comfort band (-0.5 to +0.5) without directional trends, suggesting stable thermal perceptions. Only the downward-directed airflow, which directly targeted the workspaces, showed the potential to cause thermal discomfort, warranting caution in practical applications. In Case 3, ventilation waveform patterns yielded divergent perceptual outcomes. Constant airflow achieved the highest neutrality proportions (surpassing sinusoidal and square-wave patterns), while pulsed waveforms induced greater perceptual dynamic, with sinusoidal and square-wave modulations resulting in significant TSV shifts exceeding 1.0 unit. Conversely, constant airflow eliminated transient perceptual fluctuations, reflected by a 0% dynamic perception ratio.



(a) Thermal sensation vote (TSV)



(b) Thermal comfort vote (TCV)

Figure 4 TSV and TCV of the subjects

Thermal comfort is defined as “that condition of mind which expresses satisfaction with the thermal environment”. As shown in Figure 4(b), although the mean TCV values remained within ±0.5 across all ventilation strategies, individual comfort distributions revealed more nuanced adaptation trends. During air supply position adjustments, temporal analysis over the 20-min phases revealed distinct adaptation trends. During Phase 2 (side air supply), TCV gradually decreased, whereas Phase 3 (middle air supply) restored comfort proportions. The proportion of TCV self-rated as comfortable fluctuated throughout the experiment. For air supply angle adjustment, when the angle was down, there was a decrease in the proportion, and the comfort ratio of the rest was more than 80%. In the waveform change, thermal comfort remained relatively stable, with comfort ratios consistently exceeding 80%, except at the 41-min mark. Analysis of Figures 4(a) and (b) revealed disparities between TSV and TCV. TSV mirrored immediate subjective perception of the physical environment. When different ventilation factors were adjusted, average TSV exhibited more pronounced fluctuations, and at times, neutral TSV proportions were as low as 30%. Conversely, TCV represented overall comfort, incorporating environmental feedback and psychological adaptation. Despite changes in airflow conditions, mean TCV remained below 0.5, and the comfort ratio consistently exceeded the proportion of neutral TSV, underscoring the role of human adaptability. Although the real-time changes can be felt physiologically, they can be adjusted through their adaptation, or the dynamics of variable ventilation can meet the expectations of fluctuations. These results suggest that although occupants perceived real-time environmental changes, they were able to maintain thermal comfort through adaptive processes. The dynamic nature of variable ventilation control may align with their expectations of fluctuations.

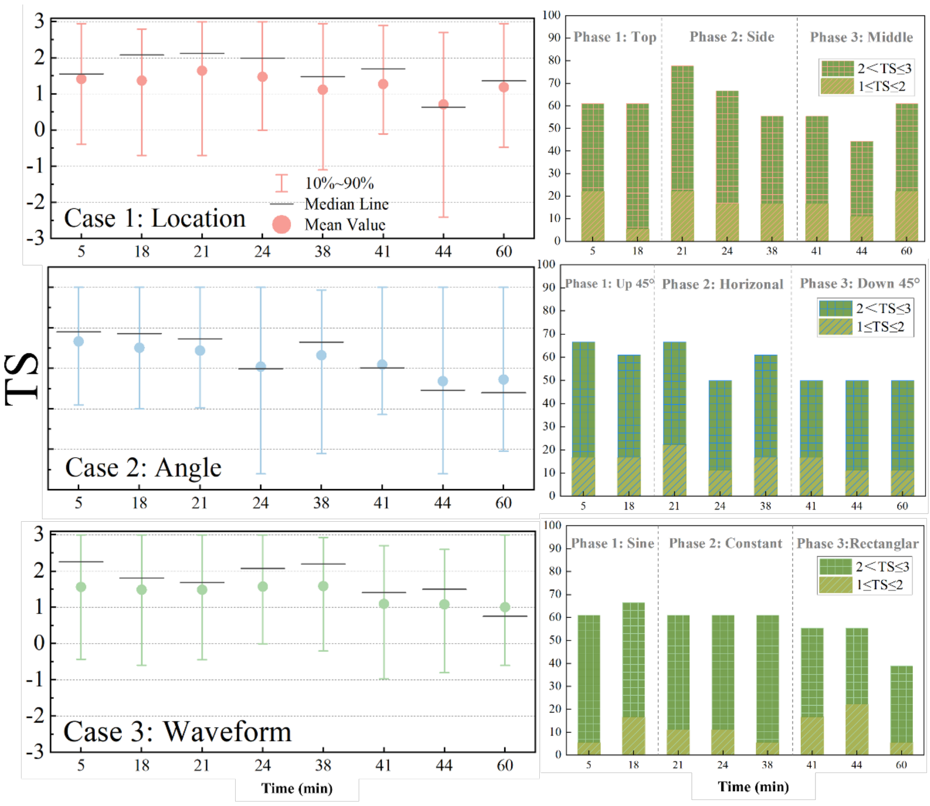
Satisfaction reflects the positive assessment of the environmental conditions by the occupants and the extent to which they feel thermally and physically comfortable. In alignment with ASHRAE Standard 55, “satisfaction” forms a core component in defining comfort.

As shown in Figure 5(a), all mean TS values are positive, indicating that there are no instances of thermal dissatisfaction. A comparative assessment of mean and median TS values shows higher satisfaction levels under Case 3-Waveform, where average TS consistently exceeds 1.0. Conversely, the most pronounced TS fluctuations were observed in Case 2 (supply air angle modulation). Notably, TS values dropped from 1.66 to 0.82 between the initial and final assessments, suggesting that angle adjustments have a more pronounced effect on TS.

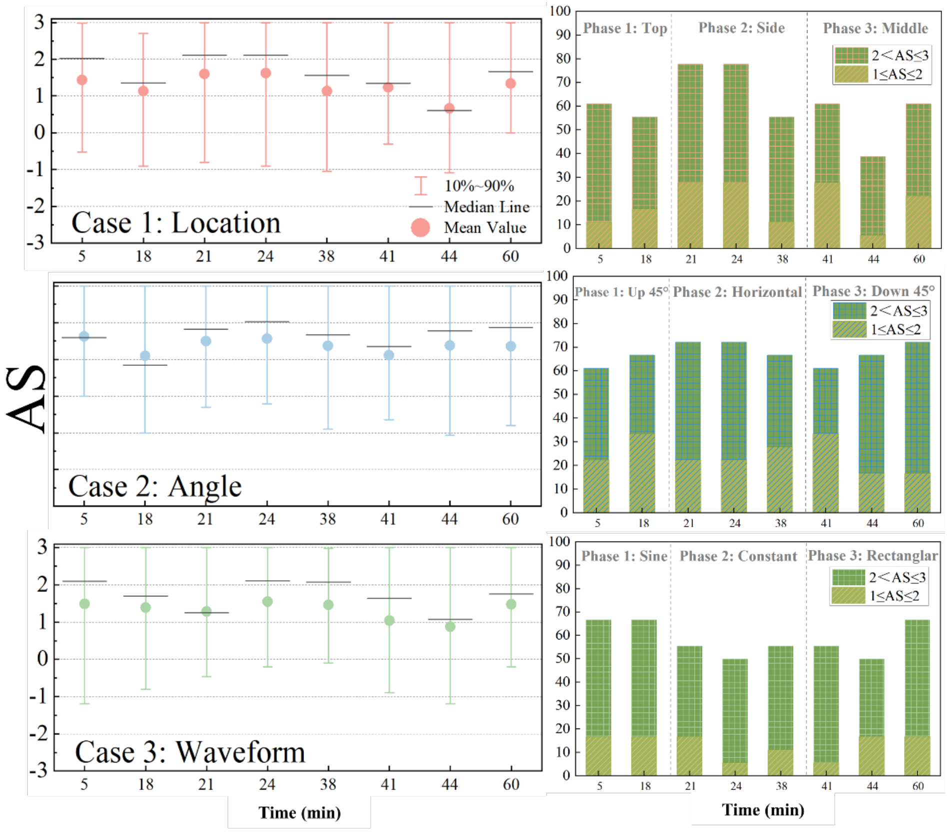
The histogram in Figure 5(a) further categorizes TS > 1.0 into two bands: "slightly satisfied to satisfied" and "satisfied to very satisfied. Compared to TSV and TCV, both TS and AS exhibited lower sensitivity to short-term changes, reflecting their composite and subjective nature. These metrics incorporate broader cognitive assessments of the environment, leading to less volatile evaluations. This reveals a dissociation between thermal and air movement sensation and overall satisfaction, indicating that the human body can adapt to minor discomfort. For instance, even if individuals perceive a thermal environment as slightly cold, they may still rate their satisfaction with it as positive.

Figure 5(b) presents the subjective evaluation results of AS. When comparing AS and TS under identical conditions, the proportional impacts of supply air position changes remained consistent between metrics. However, during supply air angle modulation, horizontal and downward 45° configurations resulted in AS proportions that were 10% to 25% higher than corresponding TS values, suggesting that participants rated airflow conditions more favorably than thermal conditions. This suggests that dynamic airflow serves as a beneficial intervention ("better ventilation than stuffiness"), fostering more lenient AS evaluations.

During waveform modulation, sinusoidal airflow maintained a strong alignment between AS and TS, maintaining comfort satisfaction levels above 60%, whereas constant airflow repeatedly produced lower AS (50%–55%) compared to stable TS. This discrepancy implies that while constant airflow promotes thermal stability, it may induce sensory fatigue, lowering overall airflow satisfaction. Sinusoidal patterns, with their periodic velocity variation, may engage intermittent human adaptation mechanisms, whereas static airflow imposes narrower AS comfort domains, constraining its evaluations.



(a) Thermal satisfaction (TS)



(b) Air movement satisfaction (AS)

Figure 5 TS and AS of the subjects

3.4 Dynamic response characteristic of variable dynamic ventilation control

Based on the above findings, insights were gained into the subjective responses of the participants to airflow and thermal variations under different ventilation control strategies. Specifically, the rate and direction of change in psychological indicators were evaluated to assess responsiveness during each of the two key adjustment periods in the experiment: before and after each adjustment (18–24 min before and after the first change and 38–44 min before and after the second change). Understanding this dynamic response characteristic is crucial for designing real-time, adaptive ventilation systems that cater to the immediate comfort and satisfaction needs of occupants, thereby promoting a user-centric indoor environment control strategy.

The rate of change in TSV over time, $\Delta TSV/\Delta t$, served as the core metric in this analysis. The sign of this value indicates the direction of the dynamic change (increase or decrease), while the magnitude reflects the intensity of the subjective response to environmental adjustments. The results are summarized in Table 3. In cases of progressive airflow adjustments (consistently increasing or decreasing flow), the signs of $\Delta TSV/\Delta t$ remained uniform. The highlighted switching and adaptation periods (highlighted in green and red, respectively) showed that environmental variability and human adaptability had predictable effects.

During location-based adjustments (Case 1), which involve more indirect dynamic changes, the signs of $\Delta TSV/\Delta t$ reversed between the switching and adaptation periods (highlighted in green and red, respectively) showed opposite effects. This indicated that over short time spans, the human body's adaptability tended to outweigh the initial abruptness of the environmental change. For airflow direction adjustments, $\Delta TSV/\Delta t$ exhibited low absolute values, suggesting minimal perceptual shifts.

To achieve significant adjustments in a brief period, adjusting the airflow angle (Case 2) proved effective. However, waveform-based airflow changes (Case 3) posed greater challenges due to their dependence on the preset oscillation period of the supply system. Although TSV values remained within the comfort range, the potential influence on work performance remains an area requiring further study. In comparison, adjustment involving air supply position (Case 1) elicited a slower subjective response compared to variations in active airflow conditions (Cases 2 and 3). This implies that, in scenarios where direct modulation of airflow parameters (such as velocity or angle variation) is not feasible, altering the supply position or adjusting occupant proximity could serve as viable alternatives to enhance thermal comfort and environmental perception.

Table 3 Dynamic response characteristics of TSV before and after change of regulatory variables

$\frac{\Delta TSV}{\Delta t}$ ($\frac{TSV\ units}{min}$) / Time	Case 1: Location of terminals	Case 2: Supply air angle	Case 3: Supply air waveform
18-21 min	0.063	-0.012	0.070
21-24 min	-0.048	-0.020	-0.012
38-41 min	0.012	-0.189	-0.155
41-44 min	-0.043	-0.049	0.004

Note: Green-filled areas represent changes in response between two switches; red-filled areas represent response changes within a brief time.

This study investigated the potential of VDVC as an active strategy for regulating microenvironmental stimuli, with a focus on its impacts on physical-environmental parameters, physiological responses, and psychological perceptions. Human subject experiments were conducted to assess three commonly adjustable dynamic ventilation factors: air supply location, angle, and waveform patterns. The main conclusions are summarized as follows:

(1) Dynamic ventilation adjustments had minimal impact on T_{forehead}, while T_{calf} exhibited the most notable fluctuations among the four monitored body parts. Changes in vent positions or airflow waveforms occasionally induced localized discomfort at the calf. However, MST remained stable throughout all conditions, with variations not exceeding 0.30°C—well within the acceptable comfort threshold. Thus, dynamic ventilation control created non-uniform airflow distribution via dynamic adjustments, but these changes did not produce noticeable differences in skin temperature perception.

(2) Subjective evaluations were more sensitive to dynamic adjustments than physiological measurements. Even without physical discomfort, TSV and TCV indicated coldness or slight discomfort, reflecting discrepancies between thermal perception dimensions. Notably, directed airflow angles toward occupants resulted in decreased thermal neutrality and lower comfort proportions. Furthermore, a mismatch between TSV and TCV was observed during the square-wave airflow phase while TSV indicated only approximately 40% thermal neutrality, TCV reflected a higher proportion of comfort level. This divergence suggests that TSV is primarily driven by instantaneous skin-level stimuli, whereas TCV reflects a cumulative perception influenced by time-averaged environmental conditions and psychological adaptation mechanisms.

(3) Compared to TSV and TCV, satisfaction levels exhibited lower sensitivity to short-term fluctuations, indicating a stronger psychological compensation effect. Adjusting vent positions similarly impacted both AS and TS; however, horizontal or 45° downward airflow angles led to a 10%–25% increase in AS relative to TS, suggesting a greater preference for actively modulated airflow environments. During sinusoidal airflow phases, both AS and TS exceeded 60% satisfaction, demonstrating convergence and a tendency toward perceived uniformity. Conversely, maintaining

constant airflow resulted in stable TS but only 50%–55% AS, likely due to monotony-induced fatigue. These results support the notion that dynamic airflow expands comfort zones through perceptual adaptation, whereas constant airflow limits comfort zones due to a lack of variability.

(4) The three dynamic ventilation strategies demonstrated distinct control mechanisms. Vent position adjustments function as psychologically adaptive control wherein air velocity strongly influences physiological responses, yet subjective evaluations decouple, emphasizing the dominant role of psychological interpretation in airflow perception. Airflow angle adjustments follow an environmental parameter-driven control model, where air velocity dominating both physiological and psychological outcomes in predictable patterns. Under conditions of equivalent mean velocity and low amplitude, filtered neural signals resulted in the central nervous system attenuating the perception of velocity oscillations below threshold frequencies, preventing conscious level.

(5) To achieve rapid intervention in sensations for prompt mitigation of occupant discomfort, adjusting the air supply angle is recommended as the most effective and responsive method. In cases where direct control over airflow characteristics is limited, adjusting the vent position could improve perception, although the effect is generally less impactful compared to changes in airflow.

4 Published Paper etc.
[Underline the representative researcher and collaborate researchers]
[Published papers]
1. Ding, X., Zhang, H., Zhang, W., Zhang, W., & Xuan, Y. (2025, April). A Fourier neural operator-based method for rapid prediction of 3D indoor airflow dynamics. In Building Simulation (pp. 1-17). Tsinghua University Press.
2. Zhang, H., Zhang, W., Ding, X., & Xuan, Y. (2025). Study of a novel neck-side ventilation system for reducing pollutant exposure. Building and Environment, 277, 112911.
3. Qing, Z., Zhang, W., Zhang, W., Zhang, H., & Xuan, Y. (2025, February). Influence of airflow and the location of infected individuals on occupant exposure in classrooms without mechanical ventilation during the winter. In Building Simulation (pp. 1-18). Tsinghua University Press.
4. Qing, Z., Zhang, W., Zhang, W., Zhang, H., & Xuan, Y. (2024). Effects of exhalation modes and spatial distribution of an infected person on contaminant transmission in a classroom. Energy and Buildings, 321, 114651.
5. Ding, X., Zhang, H., Zhang, W., & Xuan, Y. (2024). Rapid prediction of transient particle transport under periodic ventilation using a non-uniform state Markov chain model. Energy and Buildings, 321, 114666.

[Presentations at academic societies]
1. Thermal responses and comfortable evaluations under variable dynamic environment: a case study of MAV-Zhang, Weijia; Zhang, Weirong; Zhang, Haotian; Xuan, Yingli; Qing, Zhixi; Ding, Xiaoxiao-ROOMVENT2024-Stockholm, Sweden

[Published books]
N/A

[Other]
N/A

5. Research Group
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2.	Xiaoxiao Ding	PhD student	Beijing University of Technology

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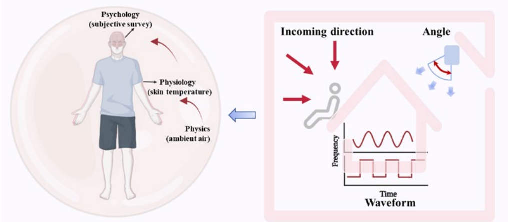
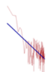
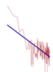
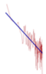
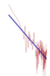
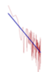
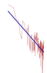
6. Abstract (half page)

Appropriate dynamic stimuli in indoor environments are beneficial to humans, yet the psychophysical mechanisms underlying differential responses to variable dynamic ventilation control remain poorly understood. To address this gap, chamber experiments were conducted to assess skin temperature and subjective responses under three varying parameters: air supply position, supply angle, and airflow waveform. Data were collected using time-sensitive questionnaires that assessed sensation, comfort, and satisfaction alongside continuous skin temperature monitoring. Results show minimal temperature fluctuations (0.22°C) under VDVC in occupied zones, with human perception mainly influenced by air velocity: position adjustment is low-frequency stable regulation ($\beta_v \leq 1.0$, TI < 27.4%), angle adjustment mimics natural wind with medium-frequency dynamics ($\beta_v \approx 1.30$, TI < 35.2%), and waveform adjustment induces high-frequency strong disturbances (TI < 38.6%, $TA\Delta_{urel}(t) > 50\%$). Physiologically, forehead skin temperature remained largely stable. However, variations in air supply position and waveform resulted in localized thermal discomfort, particularly at the calf. Despite this, mean skin temperature fluctuations remained within a thermally comfortable range of 0.30 °C. Subjective evaluations revealed heightened sensitivity to dynamic adjustments rather than physiological responses. Even in the absence of physical discomfort, thermal sensation votes and thermal comfort votes reflected perceptions of coldness or slight discomfort. Furthermore, short-term changes had a limited influence on satisfaction levels. By comparing three-level results, vent position adjustments emphasized psychological adaptation, whereas angle adjustments were more influenced by environmental parameters. Low-amplitude waveform changes were mean - dominated, with a threshold effect for wind speed perception. For rapid sensation interventions, adjusting the supply angle is advised, whereas vent position adjustments are recommended when airflow changes are restricted. this study expands the scope of dynamic ventilation from energy efficiency to occupant - centric regulation.



Ventilation controllable variables and three feedback levels

	Case 1: Position		Case 2:Angle		Case 3:Waveform	
	1st switching: 18-22min	2nd switching: 38-42min	1st switching: 18-22min	2nd switching: 38-42min	1st switching: 18-22min	2nd switching: 38-42min
TI (%)	27.4%	22.5%	35.2%	33.0%	38.6%	31.1%
Power spectrum of velocity						
β_v	1.068	0.527	1.287	1.374	1.369	1.293
$TA\Delta u_{rel}(t)$	36.9%	29.3%	28.0%	34.5%	56.9%	24.2%

Airflow fluctuation characteristics under different dynamic ventilation control