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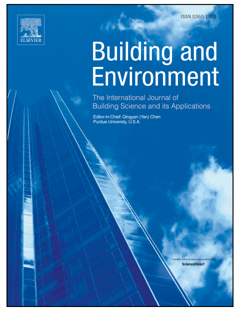

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Thermal and draught perception in fluctuating stratified thermal environments with intermittent impinging jet ventilation

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Abstract

This study proposes a new integrated air supply strategy of impinging jet ventilation (IJV) and intermittent airflow to improve indoor thermal comfort. Vertical thermal stratification is created by the IJV, and a fluctuating thermal environment is created by the intermittent airflow. Three pulsating periods (3 minutes, 5 minutes, and 7 minutes), two supply air temperatures (18 °C and 16 °C), and four air supply velocities (1.8 m/s steady, 1.5/2.1 m/s, 0.9/2.7 m/s, and 0/3.6 m/s) were designed. In both steady and fluctuating indoor environments, fifteen college students were asked to report their perceptions of thermal sensation, thermal comfort, thermal preference, ankle air movement acceptability and preference, and perceived air quality. The results showed that pulsating airflow could lower the mean air temperature above 0.6 m and raise it below 0.6 m. Furthermore, pulsating airflow could reduce overall and local thermal sensation by up to 0.21 and 0.28 scale unit, respectively, and the thermal sensation difference between the head and the foot by up to 0.23 scale unit. While in neutral thermal conditions, the pulsating period of 3 minutes had the best cooling effect of the 10 cases, but the corresponding percentage of mean dissatisfied ankle draught was 4.3% higher than in the steady operation case. Draught sensation is so closely related to ankle thermal sensation that extending the pulsating periods to 5 or 7 minutes could reduce ankle draught risk by up to 12.3%. The perceived air quality did not differ significantly between the steady and intermittent cases. The intermittent operation of IJV was shown to have superior cooling performance in order to improve indoor thermal comfort.

Keywords:

Thermal comfort, impinging jet ventilation, intermittent air supply, fluctuated thermal environment, draught sensation

Abbreviations:

ACH	Air change rates per hour
AHU	Air handing units
ATS	Ankle thermal sensation
DR	Draught risk
DR_{av}	Averaged draught risk during the test, %
DR_{pf}	Draught risk at pulse fall duration, %
DR_{pr}	Draught risk at pulse raise duration, %
IJV	Impinging jet ventilation
LTS	Local thermal sensation
MV	Mixing ventilation
OTS	Overall thermal sensation
PMV	Predicted mean vote
RH	Relative humidity, %
TCV	Thermal comfort vote
TSV	Thermal sensation vote
P_f duration	Pulse fall duration
P_r duration	Pulse raise duration
S_{av}	Averaged scores of air movement acceptability

S_{pf}	Quantified score of air movement acceptability at pulse fall duration
S_{pr}	Quantified score of air movement acceptability at pulse raise duration
T_a	Averaged occupied zone temperature (seated), °C
$T_{s\text{-}pf}$	Supply air temperature at pulse fall duration, °C
$T_{s\text{-}pr}$	Supply air temperature at pulse raise duration, °C
$\Delta TS_{head\text{-}foot}$	The difference in thermal sensation between head and foot
$V_{s\text{-}pf}$	Supply air velocity at pulse fall duration, m/s
$V_{s\text{-}pr}$	Supply air velocity at pulse raise duration, m/s
τ_{puls}	Pulse duration in minutes, min

1. Introduction

Mechanical ventilation is commonly used to ventilate a building space in order to provide a desirable indoor environment for human health and comfort. Ventilation methods are classified as fully mixed or non-uniform based on the characteristics of the airflow [1, 2]. Based on mixing and dilution, mixing ventilation (MV) may be the most representative method, but the fully mixed method produces unnecessary cooling outside the occupied zone. Because of its stratified thermal environments, non-uniform ventilation has a more effective cooling performance than MV [3].

Impinging jet ventilation (IJV) is a non-uniform ventilation method that has gained popularity in recent years for office cooling [4, 5]. The IJV air supply outlet is located on a side wall or in a corner above the floor. The high-velocity airflow is discharged downwards and strikes the floor, forming a thin layer of airflow that spreads in all directions. Thermal stratification occurs when the cool air layer is heated by indoor heat sources [6].

Few studies examined subjective thermal comfort in an IJV-ventilated space, but many studies predicted indoor thermal comfort using objective air parameters [7-10]. They came to the same conclusion: the draught sensation at the ankle and the temperature difference between the head and feet were the most important factors influencing occupants' thermal comfort. Hu et al. [9] discovered that both supply air parameters and indoor cooling load influenced the vertical temperature difference. Haghshenaskashani et al. [10] investigated the vertical temperature difference in an IJV system with and without ceiling exhaust numerically. In most cases, the results showed a satisfied indoor vertical temperature difference of less than 2 °C for ceiling exhaust. Wu et al. [11] investigated the effect of the direction of vertical air temperature differences on human thermal comfort. The 16-subject study found that subjects were more sensitive to vertical temperature differences at the upper body part in warm environments. Liu et al. [12] conducted laboratory tests to explore four vertical temperature gradients. The results suggested that the allowable vertical temperature difference between the head and feet could be 5 °C when the subjects were thermally neutral. For seated people, the ASHRAE guidebook [13] and the international standard [14] require a vertical temperature difference of less than 3 °C and a draught risk (DR) of less than 20%.

Melikov et al. [8] discovered that approximately 24% of occupants were bothered by draught sensations on a daily basis in a field study with 227 occupants. Schiavon et al. [15] assessed the DR of thirty young females with uncovered ankles and found that unacceptable air movement could range from 23% to 57%. Zhou et al. [7] assessed DR under various combinations of local air temperature and air velocity to compare the protective effects of different shoe types for covered and uncovered ankles. The results showed that protecting the uncovered ankles reduced DR by 15%. Wang et al. [16] exposed eighteen human subjects to airflow for 1 hour to investigate the time dependency of DR, and the results revealed a rapid increase in DR in the first 20 minutes and a gradual increase in the last 40 minutes. Zhang et al [17] proposed a simulation framework for determining the impact of local draught conditions on overall thermal sensation (OTS). These studies were carried out to investigate the possibility of local discomfort in a cooling/heating space with constant airflow and a consistent indoor thermal environment.

Cross-flow fans use dynamic control mode to simulate natural wind in indoor spaces [18, 19]. There are numerous types of dynamic airflow, including sinusoidal [20], intermittent (pulsating or periodic) [21], and simulated natural [22]. When the mean air velocity is the same in a warm environment (27 to 30 °C), dynamic airflow can provide a greater cooling effect than steady airflow [23, 24]. According to previous research, the use of intermittent airflow had different effects on the dissatisfied percentage of air movement. Uğursal et al. [25] tested the cooling effect of dynamic airflow on forty human subjects in both neutral and warm environments. In all of the cases studied, the majority of subjects were pleased with the increased air velocity and preferred more airflow. In Tian's work [26], intermittent airflow significantly improved thermal comfort compared to steady airflow and reduced draught dissatisfaction from 34% to 8%. Tawackolian et al. [27] subjected 37 participants to intermittent cool airflow in a neutral environment and measured the dissatisfied percentage of air movement with a pulsing period of less than 30 seconds. The findings revealed that discomfort caused by air movement was greater in intermittent ventilation than in steady ventilation. Subjects preferred dynamic airflow to constant airflow in a neutral-warm environment (30 °C) and reported less dissatisfaction with the airflow. Subjects preferred constant airflow over dynamic airflow in a neutral-cool environment (26 °C), and DR was higher with dynamic airflow [28, 29].

Previous research has shown that dynamic airflow has a cooling effect on the human body in both stratum ventilation and local air supply systems. However, the cooling effects varied depending on several air supply parameters, including pulsating period, supply air temperature, supply air flow rate, and body parts that were directly exposed to the intermittent airflow. In IJV systems, the feet were the most vulnerable body part to draught sensation. The effects of intermittent airflow on foot cooling were still unclear. Meanwhile, previous studies focused on the cooling performance of limited body parts using local air supply systems while ignoring other body parts.

The integrated ventilation strategy of IJV and intermittent air supply was proposed in this study to investigate occupants' subjective thermal comfort and airflow acceptability in such a time-dependent and stratified thermal environment. Both environmental parameters and human data (perception responses and skin temperature) were collected in order to better understand the impact of a dynamic thermal environment on occupant thermal and draught perceptions. In addition, a regression model for predicting ankle draught risk was developed.

2. Methodology

2.1 Climate chamber and equipment

Subjective tests were conducted in a climate chamber under quasi-stable and transient laboratory conditions, with supply airflow rates and supply air temperature maintained continuously or intermittently. The climate chamber measures 5.4 m (length) × 4.9 m (width) × 2.6 m (height). A black curtain was draped over two double-glazed windows on the south envelope to reduce the impact of solar direct radiation on indoor thermal environments.

A circle duct (diameter=0.25 m) located at the side envelope, 0.4 m above the floor, served as the impinging jet ventilation terminal device. A 0.2 m × 0.2 m exhaust grill was installed at the suspended ceiling. To reduce the overall complexity of the laboratory system, the IJV system was operated with fresh outdoor air. An external cooling coil was assembled to the air duct to provide extra cooling performance for rapid air temperature control at the IJV outlet after the airflow volume changed at transient laboratory conditions. The chamber's envelope was constructed using polyurethane sandwich insulation panels with a low thermal conductivity (0.023 W/m·K). As a result, the indoor thermal environment was hardly affected by outdoor environments, and the thermal load of the envelope was inadequate. To simulate the external wall and provide an essential cooling load in the chamber, two electric heating panels (1.2 m × 2.2 m) were installed on the north wall, and the surface temperature was set to 32±0.5 °C. To improve surface temperature uniformity, the surface of two electric heating panels was covered with aluminium foil. Fig. 1 depicts the geometric layout of the laboratory.

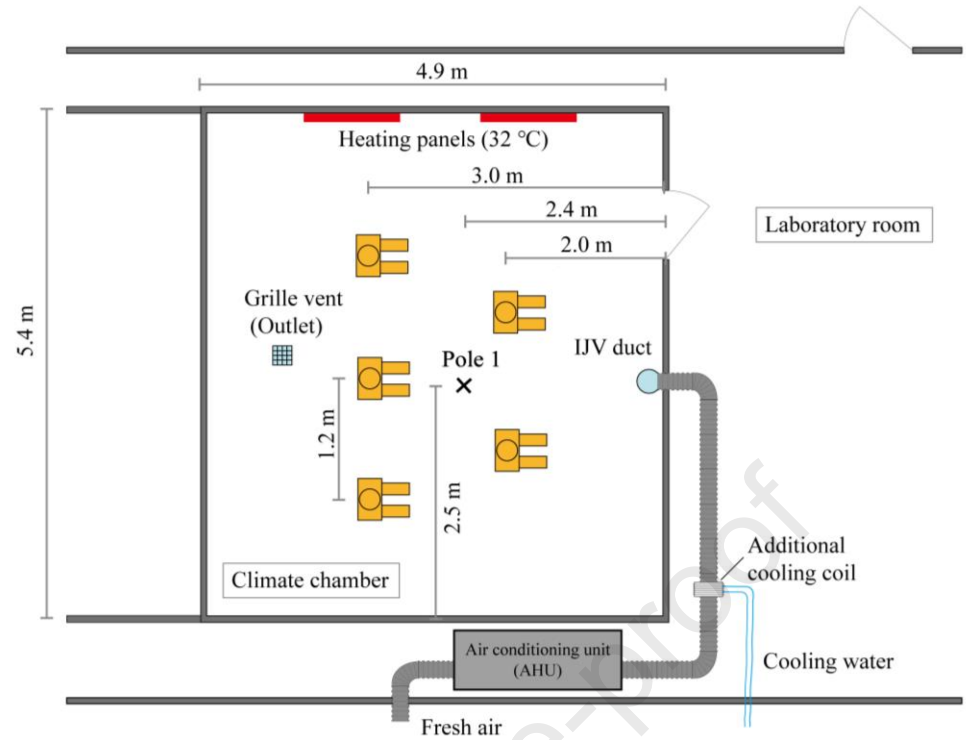


Fig. 1. The experimental process for the subjective tests.

During subjective tests, physical parameters such as local air velocity, local air temperature, globe temperature, relative humidity, and carbon dioxide were also measured (pole 1). At five vertical heights (i.e., 0.1 m, 0.3m, 0.6 m, 1.1 m, & 1.7 m), the sampling frequency for local air velocity and temperature was 10 Hz. Indoor carbon dioxide levels were measured at heights of 0.1 m, 0.6 m, 1.1 m, and 1.7 m every 10 seconds (0.1 Hz). The relative humidity and globe temperature were sampled at the same frequency of 0.1 Hz, but at different heights of 0.6 m and 1.1 m. The view factor to the occupants could be higher if the globe thermometer was placed at 0.6 m height in the centre of the five occupants, while the view factor to the envelope could be lower. The measurement of the global temperature may be affected. To reduce the effect of the human body, the globe temperature was measured at a height of 1.1 m.

Every minute, the skin temperature, which effectively represents the human thermal state, was also recorded at eleven body parts, including the head, chest, abdomen, upper arm, lower arm, hand, thigh, calf, foot, neck, and the back. The sensors were attached to the skin surface by medical tape to reduce measurement errors due to the contact thermal resistance. Table 1 shows the instrument information that was used.

Table 1. The detailed information on sampling instruments.

Parameters	Instruments	Range	Accuracy
Air velocity	Swema 03	0.05–3.00 m/s	±3% read value
Air temperature	Swema 03	10–40 °C	±0.1 °C
Globe temperature	HQZY-1	-40°C–60°C	±0.3 °C
Relative humidity	Hobo U12-012	3%–95% RH	±2.5% RH
Carbon dioxide	WEZY-1	0–5000 ppm	±50 ppm
Skin temperature	iButton DS1921H	15°C–46°C	±0.5 °C

2.2 Experiment design

The purpose of this study is to compare the cooling effect of IJV between steady and intermittent operation during the cooling season. The comparison required a neutral thermal environment, and warmer and cooler conditions were not considered. According to previous research [30, 31], the room temperature at 0.6 m height was kept between 25 °C and 26 °C to achieve thermal neutrality. Indoor relative humidity was kept between 50% and 60%.

Several studies have shown that IJV can provide stable thermal stratification in the occupied zone. As a result, IJV's steady-state operating condition was used as the reference case. The supply air temperature in the reference cases was 16 °C and 18 °C, respectively. The design air supply velocity at the IJV outlet was 1.8 m/s, implying that the air change rate in the climate chamber was 4.6 times. The fresh airflow rate was adequate for such an office with 5 occupants, with each person receiving 17.7 L/s on average. The supply air temperature was the same for the intermittent-state operating condition of IJV, but the airflow supply strategy was completely different. The supply airflow was operated intermittently for a set period of time, including the pulse raise and pulse fall durations. The supply airflow rate was kept at a higher level during the pulse raise duration, while it was kept at a lower level during the pulse fall duration. The transition from continuous to intermittent airflow may have a significant impact on human perception in the occupied zone's lower space. During the pulse fall and pulse raise durations, the designed air supply velocity was 0/3.6 m/s, 0.9/2.7 m/s, and 1.5/2.1 m/s, respectively. Despite the supply air velocity fluctuated during the pulse period in intermittent cases, the total air change rate was the same as in steady cases (i.e., 4.6 ACH).

The pulse period is another critical parameter of intermittent operation ventilation that influences the space cooling effect. Three pulsing intervals of three minutes, five minutes, and seven minutes were studied in this work to create thermal environments with different fluctuation ranges. Table 2 lists all ten investigated cases and their measured parameters.

Table 2. Experimental conditions and their levels.

No.	Measured				τ_{plus} (min)	T_a (°C)	T_g (°C)	RH (%)	CO_2 (ppm)
	$V_{s\text{-}pr}$ (m/s)	$V_{s\text{-}pf}$ (m/s)	$T_{s\text{-}pr}$ (°C)	$T_{s\text{-}pf}$ (°C)					
1	1.84±0.14	1.84±0.14	18.0±0.3	18.0±0.3	-	25.6±0.1	27.2±0.1	58.9±0.5	616±10
2	2.73±0.20	0.89±0.11	18.5±0.4	18.2±0.3	3	25.6±0.1	27.2±0.1	59.2±0.5	582±12
3	2.72±0.22	0.90±0.09	18.3±0.3	18.1±0.2	5	25.5±0.2	27.2±0.1	59.8±0.5	584±13
4	2.76±0.22	0.87±0.09	18.1±0.3	18.2±0.2	7	25.3±0.2	27.0±0.1	59.6±0.3	562±13
5	2.10±0.22	1.53±0.16	18.1±0.3	18.0±0.3	5	25.3±0.1	27.0±0.1	57.8±0.5	546±8
6	3.53±0.35	0	18.8±0.5	-	5	25.9±0.4	27.1±0.1	56.9±0.6	590±27
7	1.79±0.18	1.79±0.18	16.1±0.3	16.1±0.3	-	24.7±0.1	26.9±0.1	51.0±0.6	550±7
8	2.64±0.25	0.89±0.12	16.2±0.5	16.7±0.3	3	24.7±0.1	26.7±0.1	52.7±0.5	542±9
9	2.69±0.24	0.93±0.10	16.2±0.5	16.5±0.3	5	25.0±0.3	27.2±0.1	51.7±0.6	518±23
10	2.66±0.24	0.93±0.09	16.3±0.4	16.4±0.2	7	25.0±0.3	27.1±0.1	52.6±1.0	526±22

Note: -, not applicable; $V_{s\text{-}pr}$, supply air velocity at pulse raise duration, m/s; $V_{s\text{-}pf}$, supply air velocity at pulse fall duration, m/s; $T_{s\text{-}pr}$, supply air temperature at pulse raise duration, °C; $T_{s\text{-}pf}$, supply air temperature at pulse fall duration, °C; τ_{puls}, pulse duration in minutes, min; T_a, averaged occupied zone temperature (seated), °C; T_g, globe temperature, °C; RH, relative humidity, %; CO_2, the concentration of carbon dioxide in occupied zone (seated), ppm.

2.3 Subjects

To reduce the impact of regional thermal acclimation on the test results, fifteen young college students (8 males and 7 females) who had lived in Xi'an (latitude 34.2658° N, longitude 108.9541° E) for at least two years were paid to take part in the tests. Table 3 tabulates detailed information on the human subjects. Before the tests, all subjects were told about the precautions to take during the tests, but not about the tested conditions, which are hidden from the subjects. Furthermore, the subjects were instructed to stop eating two hours before the tests, and alcohol and caffeine were not permitted. Subjects were required to dress in typical summer attire, which included a short-sleeved shirt, a knee-length skirt or a pair of knee-length trousers, underwear, and sandals. The total insulation of the clothing ensemble is 0.54 clo.

Table 3. Anthropometric data (mean± SD).

Gender	Sample size	Age (year)	Height (cm)	Weight (kg)	BMI (kg/m^2)	I_{cl} (clo)
Males	8	24.6±1.8	179.8±5.8	76.8±12.2	23.6±2.5	0.54
Females	7	23.4±0.9	164.0±3.1	54.1±6.7	20.2±2.9	0.54
All	15	24.1±1.6	172.5±9.4	66.2±15.2	22.0±3.2	0.54

Note: BMI, body mass index; I_{cl}, clothing insulation.

2.4 Experimental procedure

Fig. 2 depicts the detailed process of each trial test, and each test takes 70 minutes. To achieve the design states, the indoor temperature was conditioned by supply air two hours before the tests began. All subjects were instructed to arrive at the preparation room 30 minutes early to attach the iButtons to the appropriate skin surface. Following preparation, subjects entered the climate chamber and were randomly assigned to one of five seats (see Fig. 3). The subjects then spent 30 minutes on thermal adaptation before reporting their thermal evaluation via paper questionnaire every few minutes for the next 40 minutes. The interval between questionnaires was not constant and varied according to the cases tested. The questionnaire was sent every 5 minutes under steady-state operating conditions. For intermittent-state operating conditions, however, the questionnaire interval was determined by the fluctuation of airflow rate, i.e., in accordance with pulsing intervals of 3-minute, 5-minute, and 7-minute. In addition, a supplementary questionnaire was placed in the middle of the 7-minute period. The inconsistent questionnaire interval between cases contributes to capturing thermal variation during intermittent operation, whereas the consistent questionnaire interval of all cases may result in thermal response at various points throughout the cycle time. During the tests, they were required to sit still or read in order to maintain a metabolic rate of about 1.0 met.

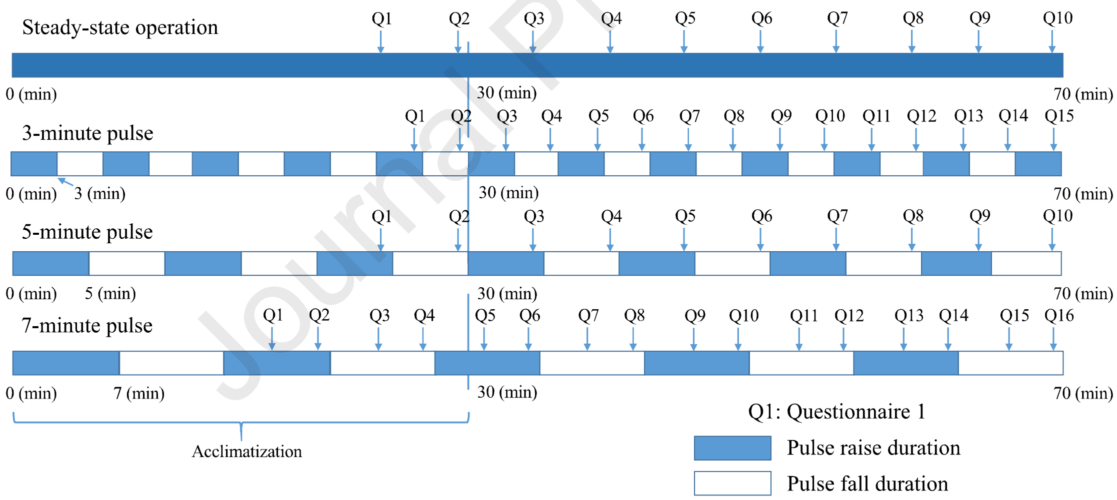


Fig. 2. The experimental process for the subjective tests.

The questionnaire assisted subjects in quantifying their assessments of the current thermal environment. The ASHRAE 7-point scale was used to assess overall thermal sensation and local thermal sensation (head, back, torso, arm, calf, and ankle). Thermal comfort ranged from slightly comfortable (+0.1) to very comfortable (+1.0) and discomfort ranged from slightly uncomfortable (-0.1) to very uncomfortable (-1.0). Subjects rank thermal acceptability on a continuous scale ranging from slightly acceptable (+0.1) to acceptable (+1.0) or from slightly unacceptable (-0.1) to unacceptable (-1.0). Then they stated whether they wanted the thermal environment to be cooler, unchanged, or warmer. The continuous acceptability scale, similar to thermal acceptability, was used to assess draught sensation at the calf and ankle region, as well as perceived air quality. They also stated whether they preferred less air movement, no change, or more air movement at ankle level. Air freshness was graded on a scale of 0 (stale) to very fresh (100).

Fig. 3. Participants remain seated during laboratory tests.

2.5 Statistical methods

In this study, 1830 questionnaire responses were collected. The Shapiro-Wilk normality test was used to test whether each type of data was normal. If the data was normally distributed, we used the paired t-test to compare the significance of two cases. We used the paired Wilcoxon signed-rank test to determine the significance of data that was not normally distributed. When $p<0.05$, there is statistical significance between the two cases. Because the questionnaire periods differed between the cases, the data from the first ten questionnaires in each case were used for statistical tests to keep the data balanced. OriginLab Pro 2021 (OriginLab Corporation, Northampton, MA, USA) was used for statistical analyses.

3. Results

3.1 Air velocity and temperature distribution

The pulsating supply airflow mode disrupts the consistent distribution of indoor air movement and vertical temperature. Fig. 4 depicts the time-dependent air velocity variation at ankle level (0.1 m) with four different supply airflow rates, namely 1.8 m/s for steady operation and 1.5/2.1 m/s, 0.9/2.7 m/s, and 0/3.6 m/s for intermittent operation. The average air velocity in the four cases is similar, ranging from 0.18 m/s to 0.20 m/s, and increases slightly with pulsating intensity. The above-mentioned airflow supply strategies have a more noticeable effect on the difference between the peak and trough of the local air velocity pulse at ankle level. Peak air velocity exceeds 0.2 m/s, even 0.4 m/s, under intermittent operation conditions. The local air velocity at other heights (0.6 m, 1.1m) is less than 0.1 m/s with little variation and is not depicted in the figure.

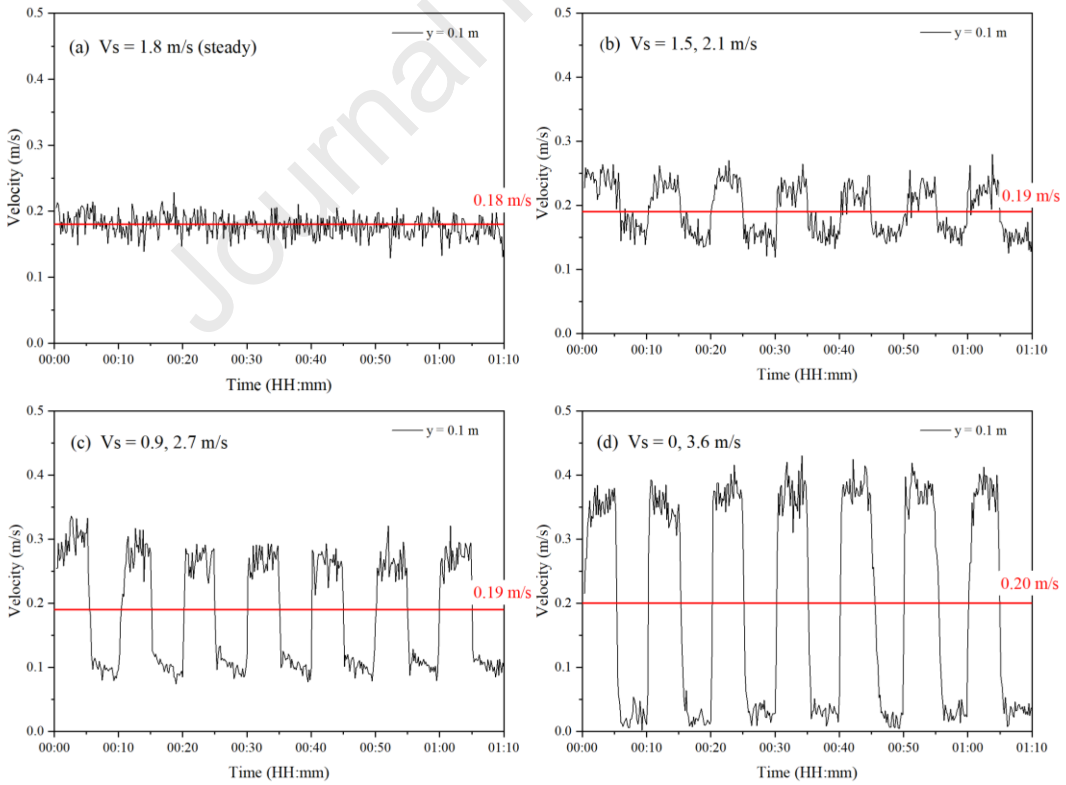


Fig. 4. Local air velocity at ankle (y=0.1 m, V_{s-pr}=18 °C): (a) Case 1; (b) Case 5; (c) Case 3; (d) Case 6.

The vertical temperature distributions from case 1 to case 6 are shown in Fig. 5. Thermal stratification is visible in both continuous and intermittent operation conditions. Except in case 6, the pulsating supply airflow has a lower influence on the temperature at 0.1 m height than the local air velocity distribution. Temperature fluctuation effects are visible at other common heights (0.3 m, 0.6 m, 1.1 m, and 1.7 m), and the fluctuation cycle is almost identical to the air supply pulsation. Temperature fluctuations at high altitudes have a greater hysteresis than at lower altitudes. The intensity of temperature fluctuations is influenced by the air supply pulsating periods, which vary from 0.3 °C to 0.6 °C at different heights under the 3-minute pulsating period and between 0.8 °C and 1.5 °C under the 7-minute pulsating period. The intensity of temperature fluctuations is also affected by the distribution strategy of supply airflow rate; the greater the difference between $V_{s\text{-}pr}$ and $V_{s\text{-}pf}$, the larger the temperature distribution fluctuations. In case 6, the stopped air supply method at pulse fall duration causes noticeable fluctuations at all five heights, particularly at 0.1 m. In general, intermittent air supply strategies raise the mean air temperature by 0 °C to 0.9 °C at low elevations (0.1 m and 0.3 m) while decreasing it by 0 °C to 0.6 °C at high elevations (0.6 m, 1.1 m, and 1.7 m).

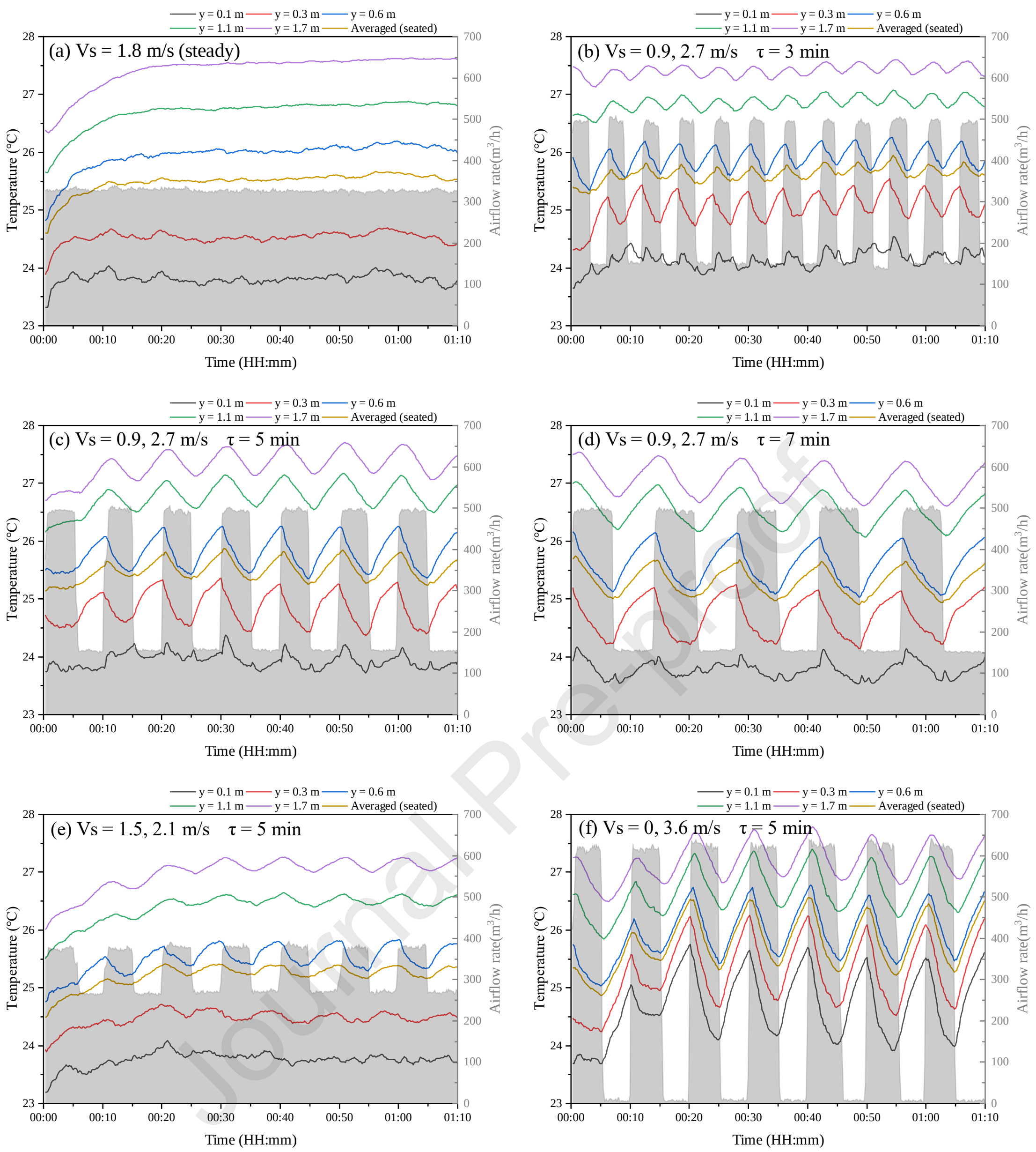


Fig. 5. Vertical temperature distributions (V_s=18 °C) : (a) Case 1; (b) Case 2; (c) Case 3; (d) Case 4; (e) Case 5; (f) Case 6.

3.2 Thermal comfort evaluation

3.2.1 Overall thermal sensation vote (OTS)

The thermal sensation differs from that experienced in stable thermal environments due to the regular fluctuations in local air temperature and velocity. Fig. 6 shows how the pulsating period and supply air distribution strategies affect the overall thermal sensation votes. The responses of fifteen subjects are averaged and displayed as a boxplot at each pulsating duration. Despite the possibility of a variable thermal environment, the OTS in all cases is normally distributed (p>0.05). Reduced supply air temperature significantly reduced mean OTS by 0.13 and 0.09 (p<0.001) under steady operation and intermittent operation (τ=3 min). However, for the pulsating periods of 5 and 7 minutes, the lower supply air temperature had no effect on OTS. When compared to the steady operating condition, the intermittent operation of IJV reduced mean OTS by 0.11 to 0.21 scale unit (p<0.01). The most effective drop in OTS exists in the 3-minute pulsating period, and increasing the pulsating period reduces the drop in OTS, but statistical significance remains. However, using intermittent airflow lengthens the box, causing the OTS to become more dispersed.

The magnitude of supply airflow fluctuations has a significant impact on the mean value of OTS. When compared to the steady case, the air supply strategy of 0.9/2.7 m/s performs better than the other two intermittent cases and has a high statistical significance on OTS (p<0.01). However, as airflow fluctuation intensities increase, the OTS votes become more dispersed, which means that subjects may feel much cooler in pulse raise duration and much warmer in pulse fall duration.

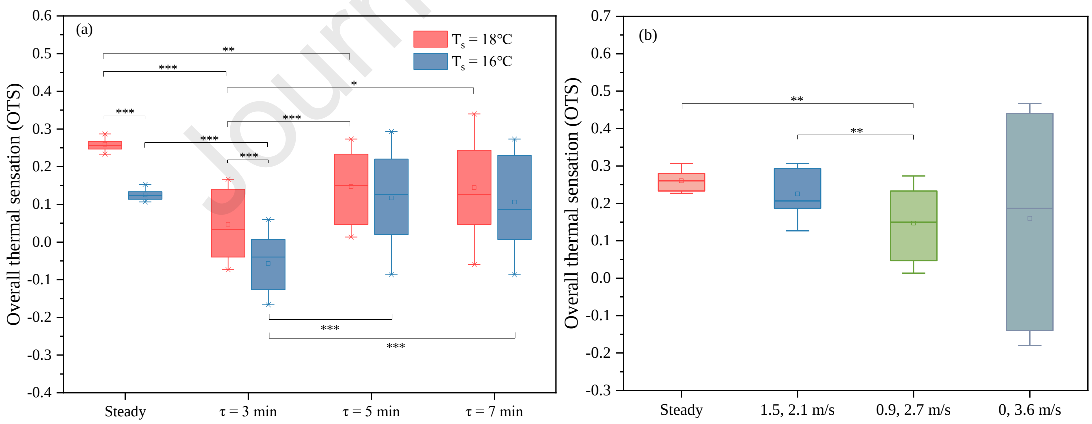


Fig. 6. Overall thermal sensations: (a) The effect of different pulsating periods; (b) Different supply air distribution strategies. The OTSV scale ranges from -3 (cold), -2(cool), -1(slightly cool), 0(neutral), +1(slightly warm), +2(warm) to +3(hot).

3.2.2 Local thermal sensation vote (LTS)

Fig. 7 depicts the LTS of various body parts (head, back, torso, arm, calf, and ankle) in various colours, with blue representing the neutral-cool sensation and red representing the neutral-warm sensation. Because of stratified thermal environments, the LST of each body part increases from the foot to the head, and the difference between head and foot in the two steady operating conditions can reach 0.51 °C and 0.46 °C, respectively. The LTS changed in two pulsating durations as the steady thermal environment changed to a fluctuating thermal environment. The continuous decrease of the indoor temperature during the pulsating raise duration (P_r duration) results in a lower vote on LTS. When compared to steady-state operating conditions, the LTS for upper body parts could be reduced by 0.07 to 0.26 scale unit at P_r duration. However, the LTS is not always decreased at P_r duration for the lower body parts (calf and foot), and the decrease in LTS ranges from -0.08 to 0.28 when compared to steady operating conditions. Except for cases 2 and 8 (τ=3 min), the LTS of each body part is always higher during the pulsating raise duration (P_f duration). In these cases, the LTS is greater than zero, indicating a neutral-warm sensation during the P_f duration, with the largest increase of 0.32 compared to steady cases. Even when the pulsating period is 3 minutes, the LTS P_f duration remains lower than that at steady conditions, with a decreasing value ranging from 0.06 to 0.17, despite the increasing indoor temperature. There is no significant difference in LTS between the two air supply temperatures (18 °C and 16 °C). When the supply air temperature is reduced from 18 °C to 16 °C, the LTS is slightly reduced (about 0.05 scale unit on average).

The supply airflow distribution strategy influences the LTS in terms of both P_r and P_f duration. When the supply airflow is close to zero at P_f duration, the LTS of each body part increases (on average from 0.15 to 0.33), because the lower airflow cannot keep the indoor air temperature at the set point. While increasing the supply airflow at P_r duration, the LTS becomes cooler (from 0.12 to -0. 01 on average), particularly at the calf and foot. Thus, the smaller the difference in supply airflow between the P_r and P_f durations, the smaller the discrepancy in LTS between the two durations.

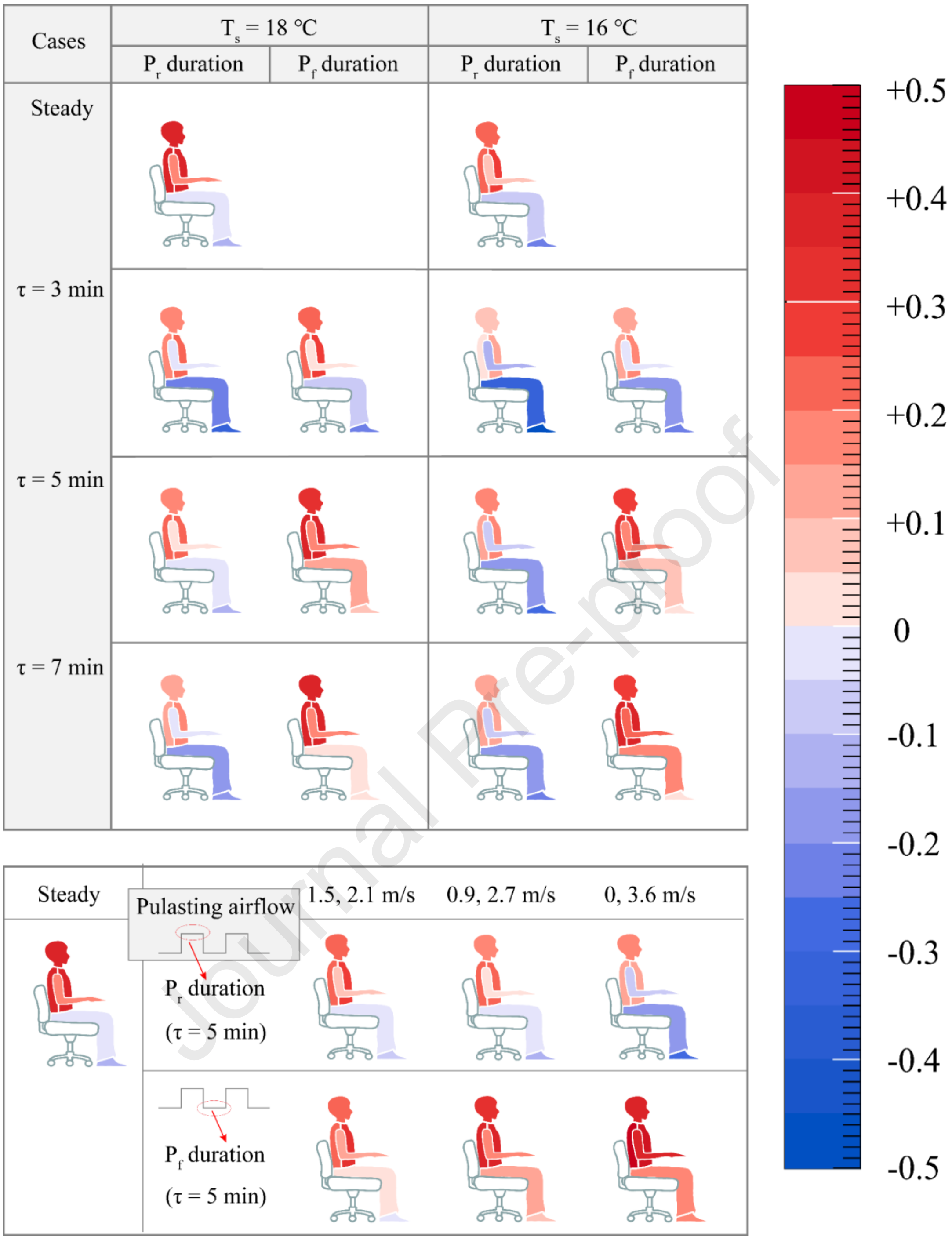


Fig. 7. Local thermal sensations of all cases (coloring for different body parts). The local TSV scale ranges from -3 (cold), -2(cool), -1(slightly cool), 0(neutral), +1(slightly warm), +2(warm) to +3(hot).

3.2.3 Thermal comfort vote (TCV)

When the steady thermal environment changed to fluctuating thermal environments, there are two distinct TCV trends at different supply air temperatures

(18 °C to 16 °C). The application of fluctuating airflow increases the mean TCV while the supply air temperature is 18 °C, and the most effective pulsating period is 3 minutes (TCV=0.38). When compared to the steady condition, the pulsating periods of 5 and 7 minutes have a minor elevation in TCV (TCVs=0.30 and 0.33, respectively). When the supply air temperature is 16 °C, the 3-minute pulsating period can slightly reduce the mean TCV but show no significant difference when compared to the steady state. The 5-minute and 7-minute pulsating periods, on the other hand, increase the median value of TCV by 0.05 and 0.08, respectively (compare to steady condition). Though increasing the pulsating period improves the TCV for the majority of thermal responses, a small portion of thermal responses may be worse.

Different supply airflow distribution strategies all increase TCV when compared to the steady state, but their effectiveness varies. When the supply airflow at P_r duration is close to that at P_f duration (1.5, 2.1 m/s), the TCV rises by 0.10 and differs significantly from the steady state ($p<0.001$). The TCV decreases as the difference in supply airflow between P_r and P_f durations increases, but still shows statistical differences ($p<0.05$ and $p<0.01$). When the supply airflow is reduced to zero at P_f duration, the mean TCV is reduced and nearly equal to that in the steady state (see Fig. 8).

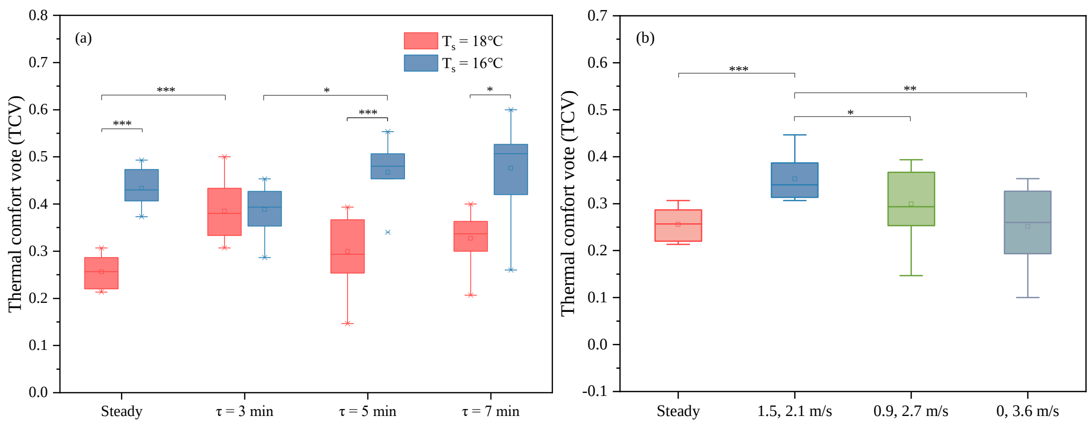


Fig. 8. Thermal comfort: (a) The effect of different pulsating periods; (b) Different supply air distribution strategies. The thermal comfort voting scale ranges from very uncomfortable (-1), slightly uncomfortable (-0.1), slightly comfortable (+0.1) to very

comfortable (+1).

3.2.4 Thermal acceptability and preference

While the ambient temperature is controlled to achieve a neutral thermal sensation, few responses report unacceptable thermal environments among the 10 tested cases, and the lowest acceptability percentage is 92.7%, indicating that fluctuating thermal environments have a high thermal acceptability. Despite the subjects' satisfaction with the thermal environments, Fig. 9 indicates the clear difference in thermal preference between the cases. Under the two supply air temperatures (18 °C to 16 °C), the reports of being cooler are reduced by 22% and 21% when the pulsating period is 3 minutes, but the reports of being warmer are increased by 5% and 6%. This indicates that the pulsating airflow every 3 minutes satisfied the subjects' cooling requirements better than the steady condition, with approximately 80% and 73% of responses preferring no change. The cooling effects are weaker when the pulsating periods are 5 and 7 minutes long, compared to 3 minutes. For example, when the T_s is 18 °C, the thermal preference (τ= 5 or 7 min) is most similar to the steady state. However, when the T_s is 16 °C, the pulsating airflow can reduce cooler preferences while increasing warmer preferences, i.e., when the pulsating period is 5 and 7 minutes, cooler preferences are reduced by 6% and 12%, respectively, while warmer preferences are increased by 5% and 7%. When the fluctuating intensity of supply airflow is increased, more requirements for becoming warmer increase from 2% to 13% (T_s=18 °C), but little changes in becoming cooler occur. It is possible that the increased airflow on P_r duration causes excessive cooling.

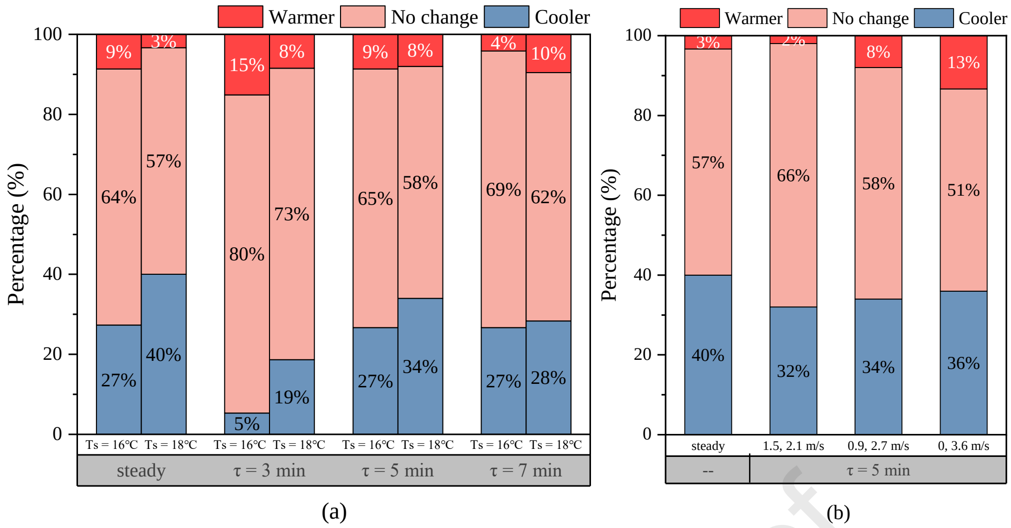


Fig. 9. Thermal preference: (a) Different pulsating periods (V_s=0.9, 2.7 m/s); (b) Different supply air distribution strategies. Thermal preference was assessed using a discrete scale (i.e., warmer, no change, and cooler).

3.2.5 Air movement perception and preference

Draught sensation is an important factor that limits the use of IJV for summer cooling. The fluctuating air movement at ankle level caused by intermittent supply airflow is shown in Fig. 4, and the corresponding response of averaged air movement acceptability and DR is shown in Table 4. In comparison to the steady cases, using intermittent air supply strategies lowers the evaluated score of air movement acceptability at the P_r duration while increasing it at the P_f duration. The percentage of DR responses could clearly explain this. The elevated local air velocity at the ankle causes a higher risk during the P_r duration, which is most noticeable when the pulsating period is 3 minutes. When T_s is 18 °C, the DR increases by nearly 10.6% during the P_r duration, but only by 4.1% and 1.2% during the P_f duration. The DR at the P_r duration could be increased by a certain level for the pulsating periods of 5 and 7 minutes (V_s=0.9, 2.7 m/s), but the DR at the P_f duration could be reduced to extremely low levels (<3%). Extending the pulsating period could reduce the DR by 4.0% to 12.3% on average, and the effects could be amplified with lower air supply temperature. Case 5 (V_s=1.5, 2.1 m/s) has a lower DR than the steady condition, but the averaged DR does not perform any better.

When the pulsating period is changed, the requirements for less air movement have a strong relationship with the averaged DR, indicating that the greater the risk of draught sensation, the more responses for reducing air movement at the calf and ankle. However, when the pulsating period is 3 minutes, the requirement for more air movement is reduced by 13.6% and 10.3%, respectively, when compared to steady conditions. When the pulsating period is increased to 7 minutes, the percentage of people who prefer more movement is similar to that of steady conditions. When the fluctuation intensity of supply airflow is increased, the requirement for more airflow movement falls from 32.7% to 24.7%, but the requirement for less air movement rises from 7.3% to 20.0%. When compared to steady conditions, the increased intensity of supply airflow partially satisfies subjects' air movement requirements but may cause more subjects to become bored with the excessive air movement.

Table 4. Draught risk votes and airflow preference.

No.	Score			Percentage of DR (%)			Preference of airflow (%)		
	S_{pr}	S_{pf}	S_{av}	DR_{pr}	DR_{pf}	DR_{av}	Less	No change	More
1	-	-	0.49	-	-	12.7	16.7	49.3	34.0
2	0.40	0.52	0.46	23.3	8.6	15.9	24.0	55.6	20.4
3	0.50	0.64	0.57	16.0	1.3	8.7	13.3	58.0	28.7
4	0.44	0.60	0.52	15.8	2.5	9.2	13.8	51.7	34.6
5	0.55	0.57	0.56	16.0	13.3	14.7	7.3	60.0	32.7
6	0.33	0.72	0.52	24.0	0	12.0	20.0	55.3	24.7
7	-	-	0.41	-	-	19.3	22.0	60.0	18.0
8	0.28	0.46	0.37	29.2	18.1	23.6	36.4	56.0	7.6
9	0.37	0.53	0.45	21.3	1.3	11.3	18.0	64.0	18.0
10	0.40	0.58	0.49	23.3	1.7	12.5	13.3	70.4	16.3

Note: -, not applicable; S_{pr}, quantified score of air movement acceptability at pulse raise duration (refer to section 2.4); S_{pf}, quantified score of air movement acceptability at pulse fall duration; S_{av}, averaged score of air movement acceptability; DR_{pr}, draught risk at pulse raise duration, %; DR_{pf}, draught risk at pulse fall duration, %; DR_{av}, averaged draught risk during the test, %.

3.3 Perceived air quality

Subjects also rated the air freshness and perceived air quality, as shown in Fig. 10. Because no extra pollutant gas is dosed in the climate chamber during the tests, the trend of air freshness votes is highly consistent with that of perceived air quality. The use of intermittent supply airflow improves perceived air quality by varying degrees ranging from 0.01 to 0.11, with 3 minutes being the most effective pulsating period. There is no discernible difference in perceived air quality among the various supply air distribution strategies. The IJV system's operations produce satisfactory air quality in all ten cases. Slightly higher perceived air quality was observed with a lower air supply temperature (i.e., 16 °C).

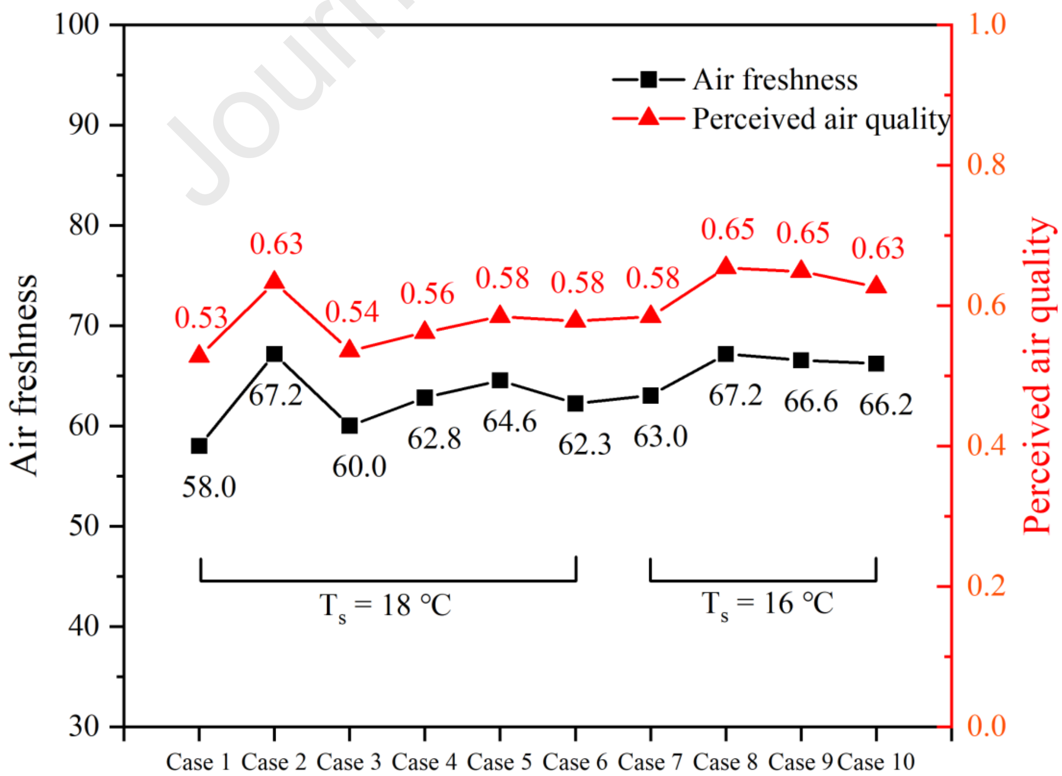


Fig. 10. Air freshness vote and perceived air quality. Air freshness was graded on a

continuous scale ranging from 0 (stale) to 100 (very fresh).

3.4 Comparison of thermal sensation with gender

The difference in overall thermal sensation between male and female participants is depicted in Fig. 11. The thermal sensation differs statistically between males and females in eight of ten cases. In most cases studied, males report higher thermal sensation values than females. When the investigated case changes from case 1 to case 10, males and females have a similar variation tendency to the thermal sensation.

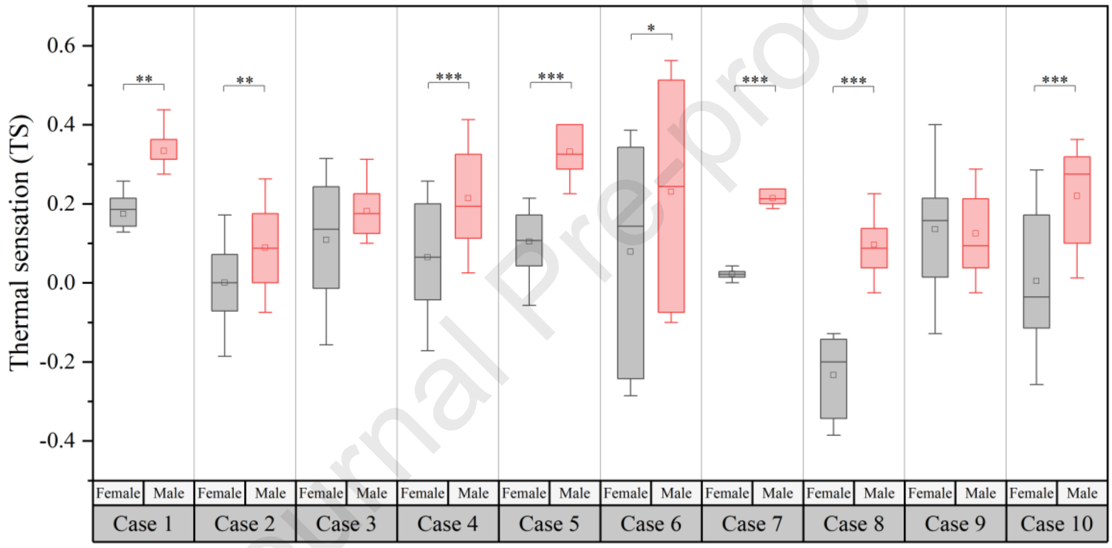


Fig. 11. Comparison of TSV with gender.

3.5 Comparison of thermal comfort between TSV and PMV

The predicted mean vote (PMV) was calculated at the occupied zone below the 1.1 m height by using CBE Thermal Comfort Tool [32]. The indoor thermal parameters from the previous 40 minutes were used in the calculation. Air temperature and air velocity were averaged by three vertical heights (0.1 m, 0.6 m, and 1.1 m). Figure 12 depicts the difference between the predicted mean vote and the thermal sensation vote in the ten cases studied. In all ten cases, PMV has a higher overall thermal sensation value than TSV, most notably in cases 1–6, which have a higher supply air temperature of 18 °C. When the IJV has a constant supply airflow, PMV and TSV have a similar distribution in cases 1 and 7. When the IJV is in intermittent operation, the largest difference between PMV and TSV exists. The PMV has a more centralized value than the TSV, which barely demonstrates the effect of fluctuating temperature and intermittent airflow on thermal sensation.

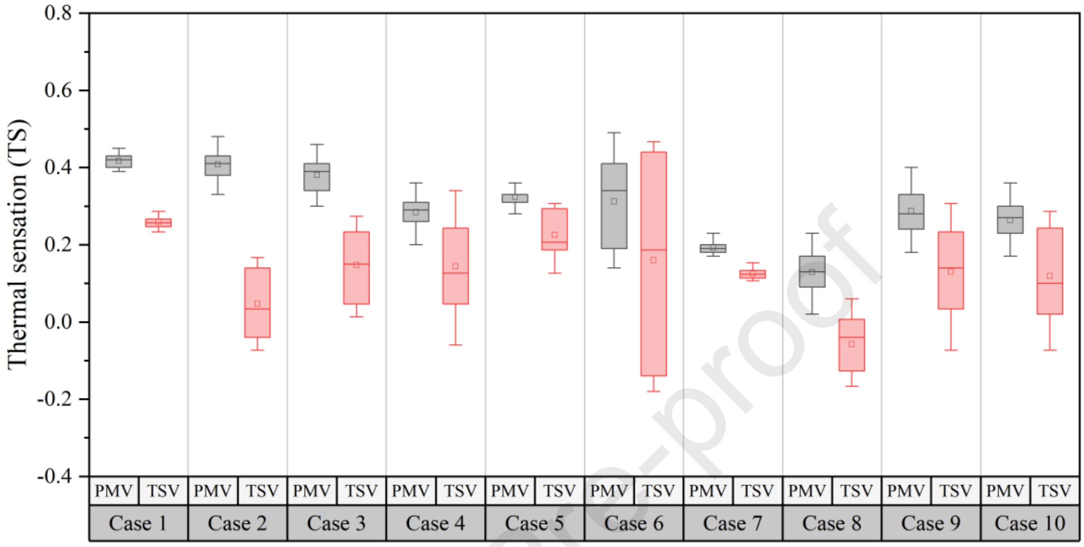


Fig. 12. Comparisons of TSV and PMV for all the cases.

4. Discussion

4.1 Subjective thermal sensation

Subjects in this study were exposed to both steady and fluctuating thermal environments and were asked to express their subjective responses to thermal sensations. The questionnaire was set to one minute before each pulsating period for intermittent operating cases, so that only the thermal sensation at the end of each pulsating period could be reported. The variation in thermal sensation is not obvious during P_r and P_f durations. The votes are changed with the fluctuating temperature distribution by analyzing the current responses to thermal sensation. The intensity of the temperature fluctuation is determined by the length of the pulsating periods, and the longer the pulsating period, the greater the variance of thermal sensation during P_r and P_f duration. When the T_s is 18 °C, the difference in overall thermal sensation could be 0.15, 0.19, or 0.21 with pulsating periods of 3 minutes, 5 minutes, and 7 minutes, respectively (refer to Fig. 6). Because of the increased airflow movement and the continued drop in air temperature, extended pulsating periods may result in excessive cooling at P_r duration and less cooling performance at P_f duration when removing indoor thermal loads. The average performance of pulsating supply airflow is better than that of steady-state operation, but the dispersible range of thermal sensation votes at different pulsating durations should be mentioned, as this may indicate poor performance in reality. The results show that the lower pulsating period of 3 minutes performs better in terms of both mean thermal sensation and dispersion. However, all of the thermal response votes were reported in quasi-neutral thermal conditions. Under neutral, cool and cold thermal conditions, the feet were found to be the most sensitive body segments [33, 34]. Cooling the feet has a reduced effect on overall thermal sensation in a warmer thermal environment [35]. In this study, a 3-minute pulsating period for intermittent air supplies improved human cooling on thermal sensation the most, but also increased the risk of draught sensation. Other studies have found that air movement helps to maintain thermal comfort in warm and hot environments [36, 37]. The intermittent operation of the IJV system may effectively cool the human body with less dissatisfaction on local air movement in a warm or a hot environment. The 5-minute pulsating period had no effect on thermal comfort when compared to the 7-minute pulsating period, which was consistent with previous findings that subjects reduced overall thermal sensation and reached steady state in less than 5 minutes [15, 38]. In warm conditions, low pulsating periods of 3 minutes or less may be recommended to achieve better thermal comfort.

According to the local thermal sensation votes, subjects feel cooler in the lower body parts (calf and foot) but warmer in the upper body parts. Cool feet and a warm head are always thought to be less comfortable [39, 40]. When compared to steady conditions, the use of intermittent supply airflow reduces $\Delta TS_{head\text{-}foot}$ (the difference in thermal sensation between head and foot) by 0.03 to 0.23, which may contribute to improved thermal comfort. Fig. 13 depicts the variation in skin temperature between pulsating periods. In intermittent operating cases, the skin temperature is higher in the chest and abdomen, and it rises with the improved pulsating period, but it is the opposite in the calves and feet. Calves have significantly lower skin temperatures than feet, which is most likely due to unwanted air cooling caused by air movement [7].

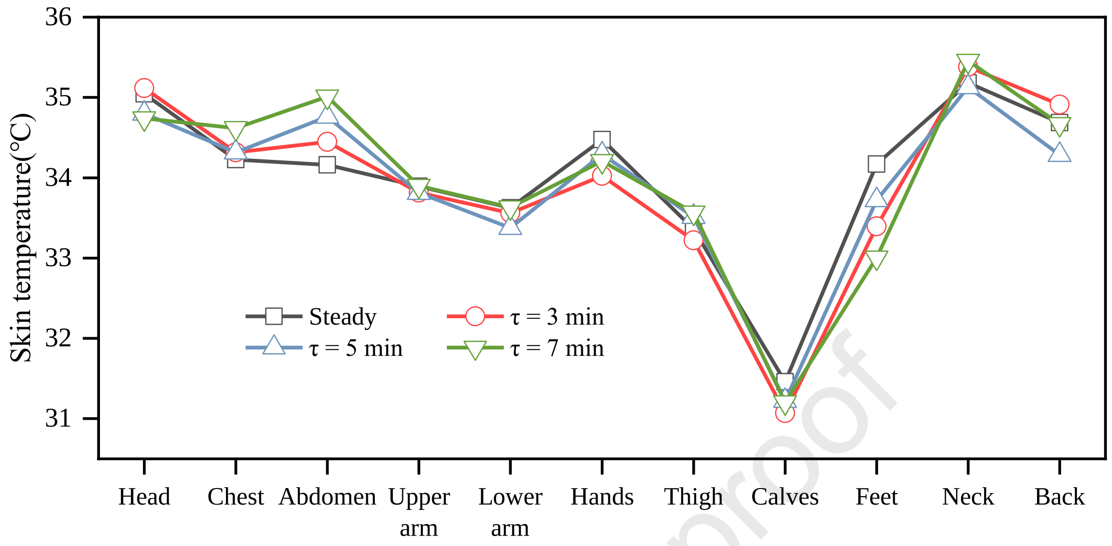


Fig. 13. Skin temperature at different body parts.

4.2 The effectiveness of PMV to evaluate dynamic thermal environments

PMV was commonly used to assess thermal comfort based on indoor thermal parameters. When the IJV system was running continuously, PMV had a similar distribution to subjects' thermal sensation votes in this study. While the PMV predicts thermal sensation better than the subjects' votes. This could be due to the average treatment of indoor thermal parameters used to calculate the PMV value. Because of the vertical temperature gradient created by the IJV system, local thermal sensations differed, which may influence the overall thermal sensation. Similarly, the averaged PMV method was unable to capture the effect of intermittent airflow on thermal sensation. Despite fluctuations in indoor air temperature and local airflow, the PMV has a more centralized distribution. In such a stratified and fluctuating indoor thermal environment, PMV may perform poorly in predicting thermal sensation.

4.3 Air movement acceptability

Fanger developed a predictive model to evaluate the DR using three parameters: local air velocity, air temperature, and turbulent intensity [41]. The air temperature and local air velocity of the investigated cases were recorded in this study, and the DR was calculated using Fanger's model. Fig. 14 compares the DR based on predicted and experimental values. It is possible that the experimental value is generally greater than the predicted value. While the predicted value is calculated using the objective values, the DR is nearly equal at all three pulsating periods (3 minutes, 5 minutes, and 7 minutes). In reality, the experimental DR has a completely different pulsating period. Taking into account the local air velocity at the ankle, the experimental value follows the same trend as the predictive value, but the experimental DR is greater.

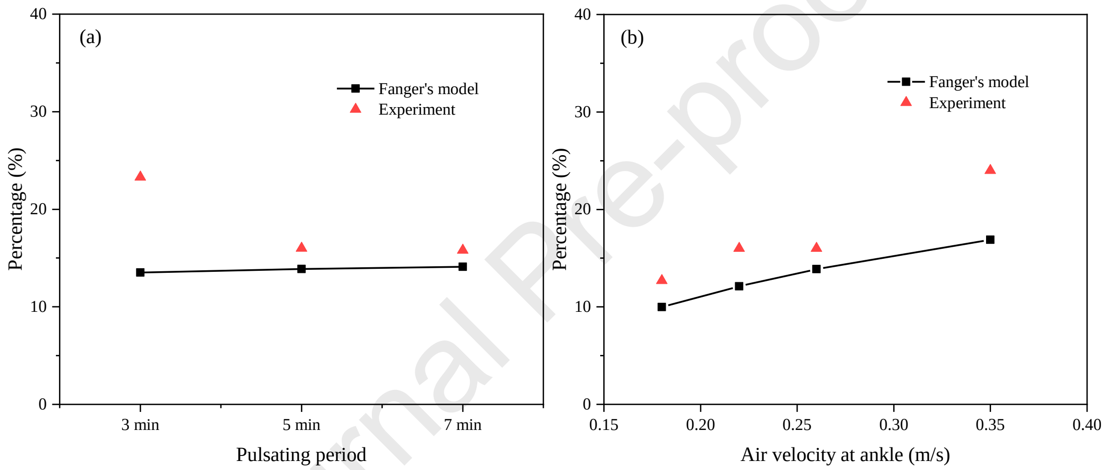
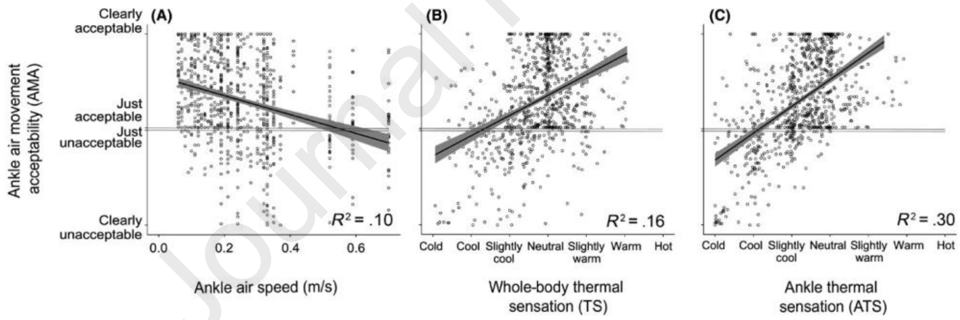
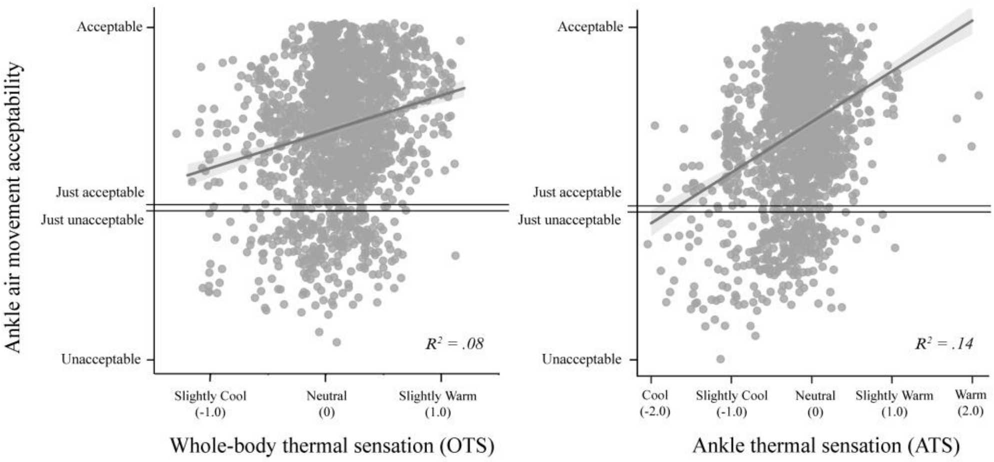


Fig. 14. The difference in DR between Fanger’s model and experimental value: (a) Different pulsating periods; (b) Different local air velocities at ankle level.

The difference in DR between the predictive and experimental values could explain the variation in thermal sensation. In general, the OTS affects the percentage of people who are dissatisfied with excessive air movement, as evidenced by numerous studies [15, 42]. Liu et al. [43] created a predictive model to assess DR at the ankle and took into account more influencing factors such as air velocity at the ankle, air temperature at the ankle, turbulent intensity at the ankle, OTS, gender, and whether lower legs are covered. The predictive model was based on ankle and OTS air velocity. Fig. 15 shows a comparison of the linear regression of draught sensation and thermal sensation in Liu's work and this study. Similar regression slopes to Liu's work were observed in this study, whether using OTS or ATS. This demonstrates Liu's model's ability to predict ankle draught risk using thermal sensation. The coefficient of determination (R^2) in regression analysis in this work was lower than in Liu's model. This could be due to the limited range of overall thermal sensation and ankle thermal sensation in this study, which kept all ten cases in thermal neutral conditions. The low R^2 could be explained by individual differences in the neutral condition. The temporal effect on draught risk was not observed because the intermittent air supply's pulsating periods primarily affect the thermal sensation (both TS and ATS). The affected thermal sensation then influences perception of air movement. The thermal sensation, rather than the pulsating periods, may have a direct influence on draught sensation. As a result, Liu's model could be used to predict ankle air movement acceptability in such a fluctuating and stratified thermal environment. In both this study and Liu's study, ankle thermal sensation has a higher fitting degree than overall thermal sensation. This could indicate that the DR at a specific body part is more dependent on local thermal sensation.



(a) Liu' s work



(b) This work

Fig. 15. The correlation between air movement acceptability and thermal sensation: (a)

Liu's model [43]; (b) This study.

4.4 Limitations

IJV systems create temperature stratification along the vertical direction resulting in different local thermal sensations. However, the supply airflows decay with the increased distance away from the IJV outlet. In this study, five subjects in a single test were divided into two rows. The different air temperatures and air velocity at two rows may influence the local thermal comfort even in the same tested condition. Prior to the subjective study, a pilot test on the indoor thermal environment was conducted at six locations that have different distances away from the IJV outlet. The results showed that, between the two rows, the decay of air velocity was limited below 0.05 m/s and the decay of air temperature was limited below 0.5 °C (at 0.1 m height). The effect of supply airflow decay could be minimized.

In this study, the pulsating periods of intermittent operating cases are longer than 3 minutes. However, in previous studies, the fluctuating frequency of dynamic airflow ranged from 0.016 Hz to 1 Hz and was provided by local devices [44]. Because of the hysteresis of the fan in the air handling unit, it was difficult to achieve in the actual laboratory conditions (AHU). In the case of all-air systems, Kabanshi [45, 46] determined that a 3-minute pulse was sufficient to destroy human thermal plumes in intermittent air jet systems. The 2-minute and 5-minute pulses with intermitted stratum ventilation systems were investigated by Tian and colleagues [26]. Thus, lower pulsating periods may have different effects on occupant thermal comfort, and lower pulsating periods may have more effects on turbulent intensity rather than thermal reduction and recovery during the P_r and P_f durations [44, 47]. This uncertainty should be resolved in future works.

The pulsating period in this work was the same during the P_r and P_f durations, and the unbalanced time allocation was not taken into account. Subjects reported cooler thermal sensations than in steady conditions and other longer pulsating periods when the pulsating period was 3 minutes, but the DR also increased. The ten tested cases were kept at thermally neutral temperatures. In warmer indoor thermal environments, the DR of fluctuating airflow can be reduced while maintaining a cooler thermal sensation. Furthermore, the exposed calves and feet may contribute to the high DR. In pulse operating conditions, keeping lower legs covered could effectively reduce the risk of draught sensation.

In most cases, thermal sensation has a high statistical significance between males and females. The results, however, may not be absolute due to the study's small sample size of 8 males and 7 females. Individual differences could be a potentially influential factor influencing the results. Gender's influence on thermal comfort should be investigated further in a fluctuating thermal environment with a larger group of related parameters.

5. Conclusions

The purpose of this study was to look into the subjective responses of occupants to the thermal environment under both steady and fluctuating conditions. Two supply air temperatures (18 °C and 16 °C), four pulsating periods (steady, 3 min, 5 min, and 7 min), and four supply air distribution strategies were considered. The results of objective thermal environments and subjective thermal comfort show that intermittent airflow supply strategies perform well. The main conclusions are as follows:

1. In comparison to the steady operation of IJV, the intermittent operation strategies could raise the mean air temperature by 0 °C to 0.9 °C at low heights (0.1 m and 0.3 m) while simultaneously lowering it by 0 °C to 0.6 °C at high heights (0.6 m, 1.1 m, and 1.7 m). With a fluctuating indoor thermal environment, the vertical temperature difference between the head and ankle could be reduced.

2. Pulsating airflow can reduce mean OTS and LTS by up to 0.21 and 0.28 scale unit, respectively, and the effects diminish with longer pulsating periods. Because of the large variation in thermal sensation during each pulsating duration, the increased pulsating periods may cause thermal discomfort.

3. At P_r duration, the fluctuating air movement may result in a higher draught risk than steady air movement, but at P_f duration, the draught risk may be reduced to nearly zero. Throughout the duration, the fluctuating airflow could reduce the draught risk by

up to 12.3%.

4. The temporal effect of intermittent air supplies for subjects could be degraded in 5 minutes. It is recommended to use pulsating periods of lower than 5 minutes to supply intermittent IJV airflow in neutral and warmer conditions to achieve a greater cooling effect on human bodies compared to constant air supplies.

5. This study's regression model of ankle draught risk is highly consistent with Liu's model, confirming its effectiveness in predicting the draught risk at the ankle.

Acknowledgements

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Highlights

- Cooling effect of IJV was investigated with consistent and intermittent airflow.
- Intermittent airflow of IJV results in fluctuating thermal environment.
- Human thermal sensation can be improved by intermittent IJV.
- Three-minute pulsating period provides the best cooling effect.
- Ankle thermal sensation is more effective in predicting ankle draught risk.

Declaration of Interest Statement

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.